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Environmental Aspects of Fluidized-Bed Combustion

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ENVIRONMENTAL ASPECTS OF FLUIDIZED-BED COMBUSTION

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16. ABSTRACT

The report reviews the environmental aspects of fluidized-bed combustion (FBC) with respect to environmental media and specific pollutants. Emissions data indicate that FBC technology is a viable alternative to conventional coal combustion. Adverse impacts on health or the environment appear to be minimal; at worst, they are no different than for conventional coal combustion systems. To support this conclusion, specific results of FBC sampling and analysis from work performed through late 1979 are discussed.

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ABSTRACT

This report addresses the environmental aspects of fluidized-bed combustion; a second companion report discusses fluidized-bed technology. The report is organized according to environmental media and specific pollutants of concern. Emissions data are presented and available bioassay results from testing of FBC effluent and emission streams are discussed. Results of sampling and analysis include data available from work performed through late 1979. Individual operating FBC test units are mentioned within this framework. A summary of the pollution control capability of fluidized-bed combustion is provided.

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1.0 INTRODUCTION

The environmental aspects of fluidized-bed combustion are discussed in this report, which is organized around environmental issues, with specific operating FBC units and/or projects mentioned only if pertinent emissions/effluent data have been generated or if important research and development are ongoing or foreseen.

Multimedia (air, water, and land) environmental impacts are discussed in the context of available emissions data and current or proposed key research. To demonstrate the potential benefits and possible disadvantages of the two alternative approaches to using FBC technology, the environmental aspects of atmospheric and pressurized FBC systems are discussed concurrently.

Figure 1 is a schematic diagram of an FBC unit that illustrates potential emission/effluent/solid waste sources. The major source of air emissions is the boiler flue gas. Minor fugitive emission sources include material transfer operations and coal and sorbent storage piles. Liquid effluent sources include boiler blowdown, cooling tower blowdown, boiler water treatment wastewater, equipment cleaning waste, and runoff or leachates from materials storage and solid waste disposal areas. The liquid waste sources are not expected to be much different from those associated with conventional power plants or industrial boilers. However, flue gas desulfurization (FGD) liquid waste can be avoided with FBC technology because *in situ* sulfur dioxide (SO_2) reduction is possible. Also, the quantities of leachate and runoff from materials and solid waste storage areas may be greater than that of conventional systems because more sorbent is used in FBC than in FGD. Solid wastes emanate from collection of flue gas particles, which consist mostly of coal ash, but more importantly, from withdrawal of spent bed material, which is partially sulfated limestone or dolomite. Typically, for a high sulfur coal with a limestone (calcium) to sulfur (Ca/S) ratio of about 4.0, FBC solid wastes are one-third fly ash and two-thirds spent bed material. An inert material such as sand can be used for fluidization, or a reactive sorbent such as limestone or dolomite can be used to fulfill the dual purpose of fluidization media and SO_2 absorbent.

Much of the available FBC environmental data have been derived from testing on small bench-scale or pilot-scale experimental units. Data from large-scale industrial-size FBC boilers are limited. Therefore, many conclusions are necessarily tentative and must be documented as full-scale FBC units come into operation. This is especially true for organic or radioactive emissions that have not been characterized, although they are not expected to be a problem. A fairly extensive data base, however, exists for criteria pollutant flue gas emissions such as SO_2 and oxides of nitrogen (NO_x). Emissions to be highlighted in following sections include those mentioned above,

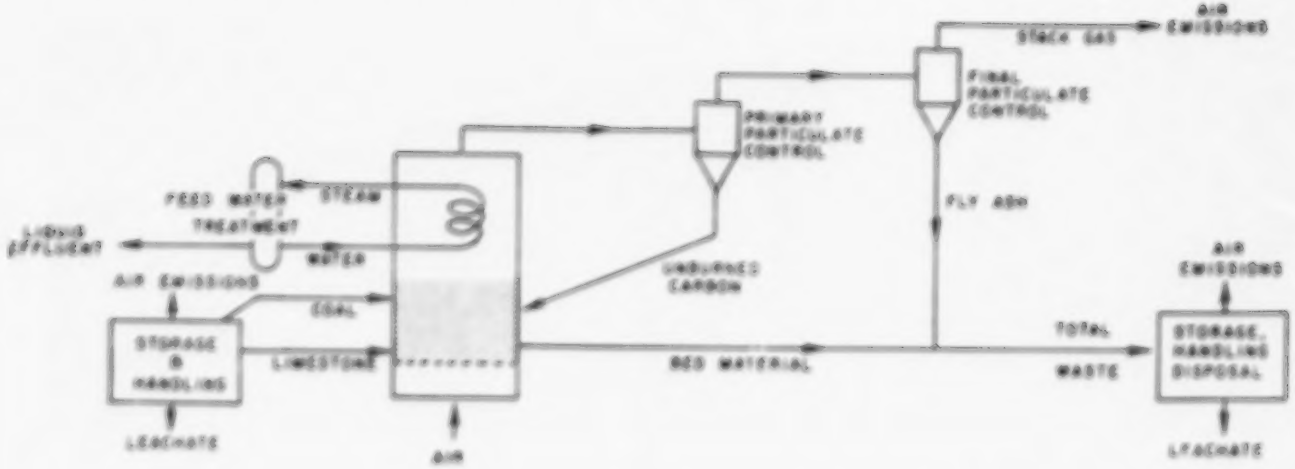

Figure 1. FBC flow diagram.

particulate matter, trace elements, and solid waste leachates. Existing health and ecological effects data based on bioassay testing are presented in a concluding subsection.

An important topic that is integral to the following discussion is an assessment of those environmental considerations that promote or deter use of FBC technology. Where possible, such qualifiers will be addressed to pressurized (P) FBC or Atmospheric (A) FBC, or utility or industrial applications. In this light, other issues that have an impact are covered including natural resource use or implications of the Fuels Use Act of 1978.[1]

2.0 AIR EMISSIONS

This section addresses major classes (mainly from a regulatory viewpoint) of FBC air pollutants. The classifications that follow include SO_2, NO_x, particulate matter, and trace elements. Organics and radioactivity are discussed in Section 5.0, addressing multimedia pollutant sources.

2.1 SULFUR DIOXIDE CONTROL IN FBC

Fluidized-bed combustion is a dual-purpose technology, incorporating gaseous pollutant reduction with combustion for raising steam. The fuel, such as coal (although an attractive feature of FBC is the capability of burning nearly any combustible material), is burned in the presence of a sorbent for in situ desulfurization.

The theoretical minimum value of the Ca/S ratio is 1; but an excess of sorbent is required because the dense sulfate layer, which forms first on the outside of the particles, retards the diffusion of SO_2 gas into the interior of the sorbent particles. The keys to low Ca/S requirements are: the diameter of the particles must be small (which requires an appropriately low gas velocity), the pores must be large enough to avoid blockage with sulfate near the mouth of the pore, and gas residence time must be increased.

An important point indicated by these requirements is the effect that residence time and accompanying sorbent particle size have on the sulfur capture effectiveness of the limestone sorbent. For example, to remove 85 percent of the sulfur, a nominal residence time of 1 second would require a Ca/S of 2.3, whereas a residence time of 0.5 second would require a Ca/S of 3.3 or an increase in limestone consumption of about 43 percent. If higher sulfur coals are being considered, this greater limestone use, which would cause a noticeable increase in operating costs, must be recognized.

Higher gas residence times can be obtained by either increasing the bed depth, decreasing the superficial velocity, or both. Increasing the bed depth increases the fan power requirements, whereas decreasing the air velocity decreases the power density, requiring larger bed areas and more complex feed systems. Thus, there is a tradeoff between capital (plan area and feed systems) and operating costs (sorbent use, fan power). The effects of operating conditions on SO_2 removal are summarized in Table 1.

TABLE 1. OPERATING CONDITIONS AFFECTING SO_2 REMOVAL

Variable increased	Effect on SO_2 removal efficiency
Sorbent reactivity	increase
Gas phase residence time	increase
Sorbent particle size	decrease
Pressure	increase

A high reactivity sorbent is the most desirable; however, high reactivity sorbent is not always available near the FBC site, and transportation of sorbent for long distances may be economically unattractive. When a sorbent has been chosen for an installation, whether it is AFBC, or PFBC, the Ca/S ratio can be reduced by designing a sufficiently high gas phase residence time (approximately the ratio of the bed depth to the gas velocity) and sufficiently small sorbent particle size.

Results of research performed by Westinghouse Research and Development point to close to optimal values for gas residence time and sorbent particle size.[2] In both AFBC and PFBC, an average in-bed sorbent particle size of about 500 μm is desirable based on thermogravimetric analyses and a desulfurization kinetics model developed by Westinghouse. Westinghouse results indicate that while using dolomite 1337 at constant operating conditions in PFBC, 90 percent SO_2 removal can be achieved with a Ca/S ratio of approximately 4.2 at 2000 μm average in-bed sorbent particle size and 1.6 using sorbent at 500 μm average in-bed particle size.[3]

To allow for the use of small sorbent particles, lower superficial velocities and recycling of bed carryover are warranted to avoid elutriation of small sorbent particles and allow for sufficient time for reaction between SO_2 and CaO. (This also enhances combustion efficiency by char recycle and longer carbon residence time in the bed.) In AFBC, a gas residence time of at least 0.67 seconds appears to be appropriate to approach optimal desulfurization performance.[4] In PFBC, where deeper beds are used to allow for more heat transfer area, Westinghouse results indicate that a gas residence time of approximately 2 seconds is appropriate to reduce sorbent use.[5] Because longer residence times are characteristic in PFBC, and because of favorable reaction kinetics under pressure, the desulfurization performance of AFBC can be matched in pressurized systems using lower Ca/S molar feed ratios.

2.1.1 Experimentation of Desulfurization in FBC

Experimental data have been developed by several investigators over the past 10 to 15 years. The available data have been obtained in FBC units from bench-scale (6-in. diameter) to small industrial-scale units ($12MW_t$),* as well

*MW_t = MW thermal input.

as by thermogravimetric analysis and mathematic projections. Generally, experimental data have shown that AFBC can achieve 90 percent SO_2 reduction with Ca/S ratios as low as 2.6 using a high reactivity sorbent.[6] PFBC has been observed to attain 90 percent reduction of SO_2 with a Ca/S ratio of less than 1,[7] although the typical range is between 1 and 2. Figure 2 shows a range of data for atmospheric and pressurized units.[8-17] The scatter in the data points is produced by diverse sorbent reactivity and unit operating conditions. The pressurized units show a significantly higher reduction efficiency with lower Ca/S ratios than the AFBC units.

The shaded area indicates the range of performance expected from AFBC systems at gas phase residence times of $\geq$ 0.67 seconds and in-bed average sorbent particles sizes of close to 500 μm. Much of the AFBC experimental data fall within the boundaries. The PFBC units all indicate a higher removal efficiency than the AFBC data. Most of the points that fall below the expected efficiencies were derived from the ANL 6-in. diameter atmospheric unit and the PER-FBM atmospheric unit. These efficiencies were lower than those expected because both units were operated at short gas phase residence times during those tests (as short as 0.13 seconds). The pressurized units, on the other hand, were run at higher gas residence times, about 2 seconds and above.

PFBC experimental units have demonstrated more efficient SO_2 removal using dolomite as a sorbent. Exxon results show that dolomite has an advantage over limestone that increases as greater levels of sulfur removal are attained.[18] Exxon estimates that a Ca/S molar feed ratio of 1.3 is sufficient for 85 percent SO_2 reduction using dolomite, and more than twice that ratio would be necessary using limestone. Projections made by Westinghouse have indicated a similar advantage.[19] Because limestone has a higher calcium content than dolomite, the difference in total material loadings between the two alternative sorbents is not significant.

2.1.2 Key Research in FBC SO_2 Control

Future research will emphasize the confirmation of SO_2 control capability in large-scale units. In addition, to verify theoretical predictions and provide guidance for future system design, the influence of gas residence time and sorbent particle size in large demonstration units must be documented. Cost/benefit tradeoffs associated with maximizing or minimizing these parameters must also be defined.

Other investigations that are of prime importance are those focusing on the assessment of limestone characteristics and availability as well as sorbent regeneration and alternative sorbents. Energy Resources Company (ERCO) has recently begun investigation of interquarry limestone characteristics.[20] This study should provide a good perspective of the effects of limestone variations. In addition, Westinghouse will be conducting a detailed investigation of intraquarry variations.[21]

The Illinois State Geological Survey has extensively studied several varieties of carbonate rock (mainly limestone and dolomite) for desulfurization

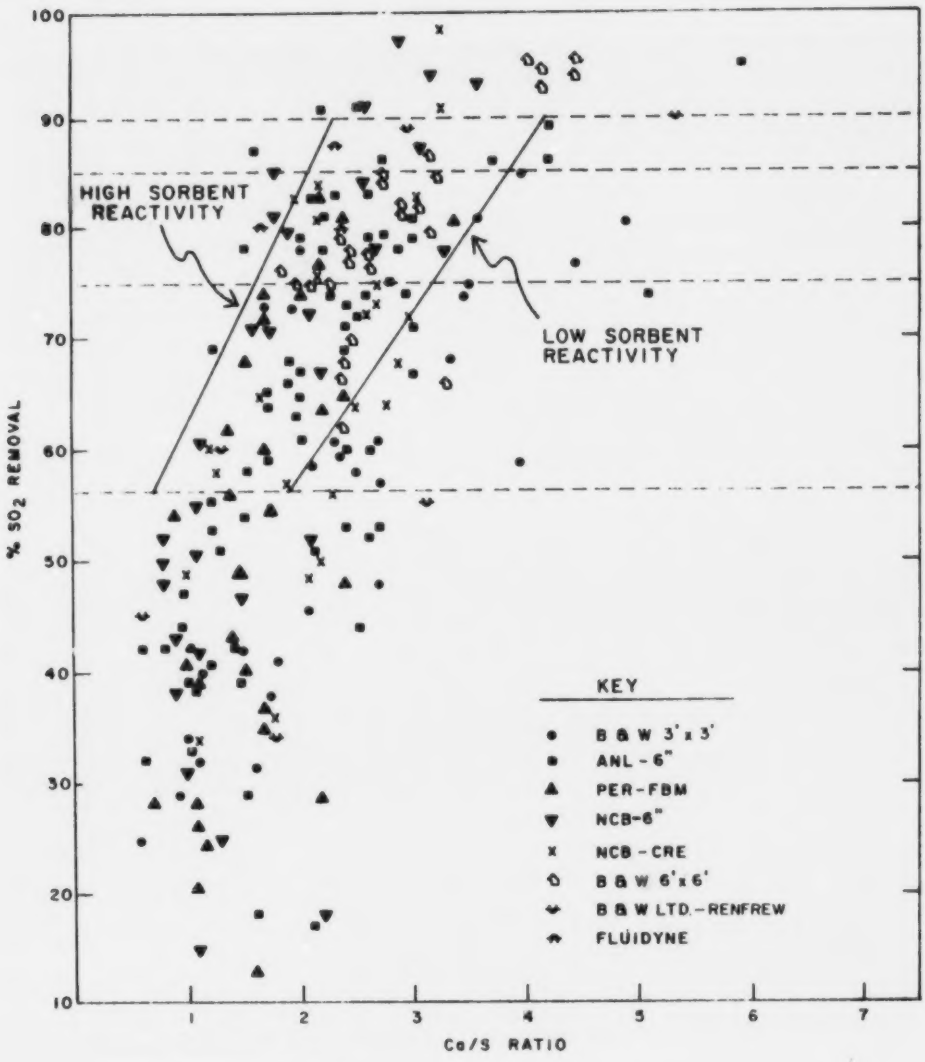

Figure 2. Summary of experimental SO_2 reduction data for AFBC and PFBC test units.[1-8]

in fossil-fuel combustion processes.[22] Samples were investigated for petrography, mineralogy, chemistry, pore structure, and surface area, revealing a wide range of petrographic and SO_2 sorptive properties. Relatively high SO_2 reactivity was found for chalks, calcareous marls, chalk, and colitic argonite sand samples, probably because of high pore volumes and fine grain size.

General Electric is conducting experiments to develop an automatic process controller for maintaining a constant percentage of SO_2 removal by the bed.[23] This capability is necessary to adjust for changing bed conditions without allowing excessive SO_2 emissions for intermittent periods. Expanded research and development in the area is expected.

Experimentation with additives for improved desulfurization has also been conducted. Argonne National Laboratories (ANL) has studied the effect of adding salt (NaCl) to the bed.[24] Although the pore surface area and calcium use are increased by the addition of salt, salt has a great potential for producing boiler corrosion. Other catalysts under consideration are iron oxide and coal ash.[25]

Westinghouse[26] has made some preliminary investigations of Na_2CO_3, $NaAlO_2$, $NaCO_3$-Fe_2O_3, and $CaAl_2O_4$ as alternative sorbents. Meanwhile, investigators at ANL are experimenting with virgin and spent oil shale.[27] Virgin shale is attractive because of its inherent heating value of about 3,000 Btu/lb.

Sorbent regeneration techniques also require further exploration and development to minimize feed requirements, spent stone disposal, and associated sensible heat loss. Exxon is attempting to develop regenerable synthetic sorbents that have good attrition resistance, high reactivity, and good regeneration characteristics.[28] Calcium aluminate cement and calcium or barium titanate both appear to have characteristics that may make these materials cost competitive with limestone. Methods for enhancing limestone reactivity by precalcining (currently under investigation at Exxon)[29] and catalyst addition are also of importance.

In essence, the thrust of current and future work is to minimize sorbent requirements and spent stone disposal so that SO_2 retention is optimized and cost, energy, and environmental impact are minimized.

2.2 NITROGEN OXIDES EMISSION CONTROL IN FBC

Nitrogen oxide emissions from fluidized-bed combustion of coal are generally lower than those from conventional systems. Design and operating factors that influence the formation and reduction of NO_x in FBC are listed in Table 2, which indicates the general trend of the effect on NO_x emissions.

TABLE 2. OPERATING CONDITIONS AFFECTING NO_x EMISSIONS FROM FBC

Variable increased	Effect on NO_x emissions
Temperature	increase
Gas phase residence time	decrease
Excess air	increase
Pressure	decrease
Fuel nitrogen content	increase
Coal particle size	decrease

The kinetics of NO_x reduction are not well defined to date. The low NO_x emissions from FBC are inherent to the system. A quantitative correlation, beyond the trends shown in Table 2, is not predictable at this time.

Figure 3 illustrates NO_x emissions data measured over the range of FBC operating conditions listed.[30-37] Certain trends are evident in the data, most apparent of which is that pressurized systems (PFBC) generally produce lower NO_x emissions than atmospheric units (AFBC). Furthermore, among the AFBC units, the larger units emit lower levels of NO_x than the smaller units. This is highlighted in Figure 4.[38] With the exception of the 6-in. diameter atmospheric unit, all the data that have been surveyed are below 301 ng/J (0.7 lb/10^6 Btu). Emissions as low as 22 ng/J (0.05 lb/10^6 Btu) have been achieved using FBC.[39] However, the reaction mechanisms are not sufficiently understood to predictably and consistently achieve these levels of control. It is expected that larger (large industrial boilers and utility-sized boilers) units will tend to generate lower levels of NO_x than smaller units. (see Figure 4). This too must be demonstrated in full-scale units.

2.2.1 Key Research on FBC NO_x Control

Research and development to characterize and effectively use mechanisms of NO_x control in FBC are proceeding. An alternative operating mode that can be used to reduce NO_x emissions even further is two-stage combustion. In conventional systems, the application of staged combustion has resulted in 30 to 50 percent NO_x reduction.[40] Further testing is required to define the NO_x control potential of two-stage combustion in FBC systems.

Studies of staged combustion have been conducted at the EPS's SATR (Sampling and Analysis Test Tig) at Research Triangle Park, North Carolina;[41] Exxon; [42] the Battelle MS-FBC[43] and the Enköping district heating plant.[44] The SATR is a small AFBC pilot plant, mainly designed for investigating particulate control. The Exxon miniplant is a small pressurized unit. The MS-FBC is a small recirculating bed FBC containing dense phase and entrained beds. The Enköping (Sweden) FBC is a two-staged combustor that generates 38,600 kg/hr (85,000 lb/hr) steam. Only the Enköping unit is specifically designed as a staged combustor, Although this unit burns oil, it nevertheless demonstrates

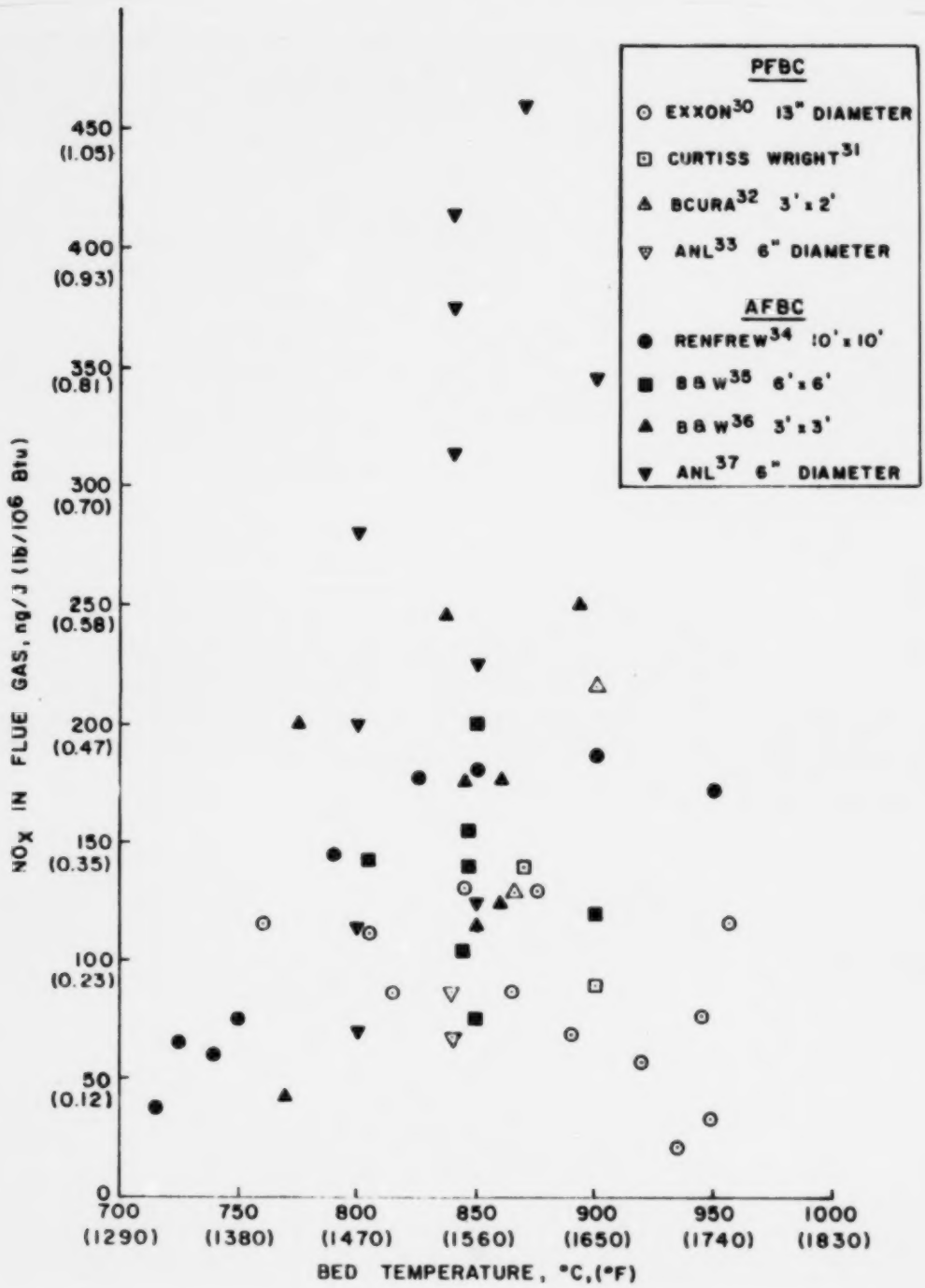

Figure 3. NO_x emissions from fluidized-bed combustion boilers.

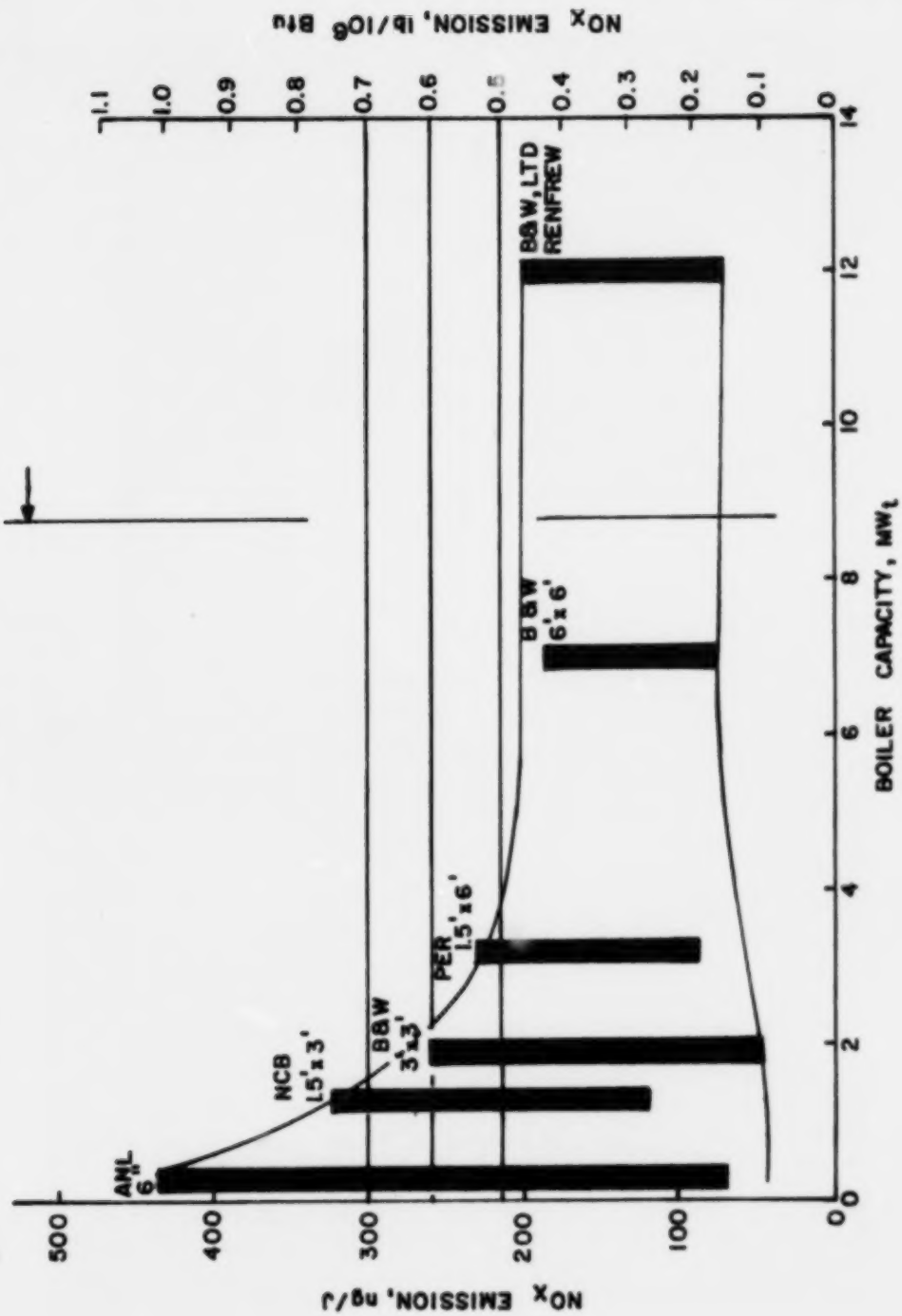

Figure 4. NO_x emissions from experimental AFBC units as a function of capacity.[38]

the use of staged combustion with FBC. Preliminary data from these units indicate low NO_x emissions although some of the units had a concurrent increase in SO_2 emissions and a decrease in combustion efficiency.

The Massachusetts Institute of Technology (MIT) has been studying NO_x emissions from FBC and has made several recommendations for combustion modifications for NO_x control based on small laboratory fixed and fluid-bed experimentation. Optional operating techniques postulated are:[45]

- inject 10 percent or more of the stoichiometric combustion air as secondary air into the freeboard for nitric oxide (NO) reduction by char in the bed and comlete combustion of carbon monoxide (CO) in the freeboard;
- inject recycled char close to the top of the bed to promote the decomposition of NO rising through the bed; and
- inject recycled char together with coal and sorbent into a shallow, uncooled bed situated above the main bed to reduce NO and produce favorable conditions for volatile combustion and sulfur retention in the "top fed" fluidized combustor.

The performance and economics of such options must be further assessed.

Further investigation of two-stage combustion in large-scale FBC units is required to ensure that suitable SO_2 control and efficiency can be attained simultaneously with low NO_x emissions. Another item to investigate is tube corrosion brought on by possibly shifting oxidizing/reducing zones in the unit.

Other techniques that could be considered for further NO control in AFBC include flue gas recirculation and ammonia/urea injection. Further testing is required to determine the incremental NO reduction that can be expected under these optional operating conditions.

If further reduction of NO_x is necessary, catalytic reduction is a possible approach. Studies have been performed using various metal oxides and metal powders. Al_2O_3 and ZrO_2 seemed to have no effect on NO_x formation, and cobalt oxide seemed to increase NO_x in testing conducted at ANL.[46] However, the addition of nickel powder to the reaction chamber showed a significant decrease in NO_x formation in testing at the University of Minnesota.[47] This particular catalyst is extremely expensive and economically unrealistic for use in FBC, yet the study does demonstrate the feasibility of using a catalyst for NO_x control.

2.3 PARTICULATE EMISSIONS

2.3.1 Generation and Control of Particulates from FBC Systems

Particles emitted from the combustion chamber of an FBC boiler are a combination of fly ash from the coal, unburned carbon, and elutriated sorbent. The amount of elutriated material is dependent on a variety of design and

operating parameters. Table 3 indicates some of the major FBC design and operating factors and how they affect particulate emissions. The table indicates trends observed experimentally that are expected when the given operating/design variable is changed; however, combinations of changes in these conditions and the degree of change could negate or reverse the trend.

Particle emissions from FBC will be controlled in a manner similar to conventional boiler particulate. Elutriated sorbent and ash properties that may affect the collectability of the ash include:

- particle resistivity,
- particle composition and morphology,
- particle moisture content,
- particle size,
- particle compressibility,
- flue gas temperature
- flue gas flow rate, and
- volume of particulate matter to be collected.

These parameters should be assessed to properly design the final particulate control system.

TABLE 3. FACTORS AFFECTING PARTICULATE EMISSIONS FROM FBC

Factor	Trend of particulate emissions
Coal	
as ash content increases	particulate emissions increase
as sulfur content increases	particulate emissions increase
as ash agglomerating characteristics are exhibited at low temperatures	particulate emissions decrease
Sorbent	
as particle size increases	particulate emissions decrease
as attrition and decrepitation increase	particulate emissions increase
Operation	
as superficial gas velocity increases	particulate emissions increase
as primary recycle is applied	particulate emissions decrease
Bed Geometry	
as bed depth increases	particulate emissions decrease
as freeboard depth increases	particulate emissions decrease

A primary particulate control device, usually a cyclone, is used to collect larger particles that have the most significant carbon content. This primary cyclone catch is often recirculated to the boiler to attain greater combustion efficiency and improve SO_2 reduction efficiency. An alternative method for increasing carbon use is to feed the collected material to a secondary FBC combustion chamber called a carbon burnup cell (CBC). The CBC is a variation of the FBC cell. Some of the ways in which it differs from the FBC cell are: the feed material (finer particles, high ash content, low carbon content), higher operating temperatures [2000°F (1100°C)], higher excess air (~50 percent) and lower fluidizing velocity. Particle emissions generally decrease with increasing temperature, probably resulting from improved carbon combustion and ash agglomeration. In some cases, large utility systems may use a CBC, although further investigation of the cost/benefit tradeoffs must be implemented. If neither of these technologies is applied, then the primary particulate control device catch is withdrawn for disposal.

The particles that pass through the primary cyclone are collected in a final control device. Final particulate control has not yet been demonstrated on AFBC units; however, conventional particle control devices should be adequate to meet present and planned emission standards. If high levels of control are desired, electrostatic precipitators (ESPs) or fabric filters will most likely be applied. If lower efficiency is acceptable, a multitube cyclone may be sufficient. Pressurized systems may require greater control efficiency because of strict limitations on the amount of particulate matter that can be tolerated in the flue gas-driven turbine that supplies about 20 percent of the PFBC output. There is some conflict of opinion on allowable levels, and the effect of particulate level on turbine life needs to be investigated further.

2.3.2 Experimental Data on Particulate Emissions from FBC

Actual test data demonstrating the efficiency of final particulate control devices applied to coal-fired AFBC boilers are not available at this time. Particulate emissions data that do exist generally represent loadings in the flue gas to, and the exhaust from, primary cyclones applied to the FBC. To date, large AFBC units have not operated long enough to demonstrate final particulate control technology. PER,[48] ANL,[49] NCB[50] and B&W[51] have reported emissions under varying conditions. The results are summarized in Table 4.

TABLE 4. AFBC PARTICLE COLLECTION EFFICIENCY SUMMARY

Unit	Control device	Range of efficiency
ANL 6" bench scale AFBC	primary cyclone	86 - 90%
ANL 6" bench scale AFBC	combined cyclones (2)	97 - 99%
NCB CRE pilot scale AFBC	combined cyclones (2)	95 - 98%
PER 12" x 16" FBC	primary cyclone	~ 90%
PER 18" × 72" FBM	primary cyclone	90 - 95%
B&W 3' × 3' FBC	wet scrubber (primary)	50 - 80%
B&W 6' × 6' FBC	primary cyclone	50 - 91%

The emissions associated with these collection efficiencies range from 108 ng/J (0.25 lb/10^6 Btu)[52] using primary and secondary controls to a maximum of 15,215 ng/J (35.39 lb/10^6 Btu).[53] The highest level was measured after a low efficiency (50 percent) primary control device over a shallow bed using pulverized limestone as feed.

Particulate emissions from PFBC have been measured at the Exxon Miniplant and the National Coal Board-Coal Utilization Research Laboratory (NCB-CURL). At Exxon, particulate emissions in the flue gas after two stages of cyclone cleanup averaged about 860 ng/J (2.0 lb/10^6 Btu) with a mass mean particle size of 3 to 6 microns.[54] The collected material from the primary cyclone was recycled to the bed to improve carbon combustion efficiency. The second stage cyclone was found to have an overall collection efficiency of 85 percent. Applying three stages of cyclones in test series, flue gas loadings exiting the third stage were between 11 and 44 ng/J (0.026 to 0.10 lb/10^6 Btu).[55] The lower measurement of 0.026 lb/10^6 Btu is below the current new source performance standard (NSPS) for coal-fired utility boilers of 13 ng/J (0.03 lb/10^6 Btu).

Particulate emissions were measured at the NCB-CURL 3-ft x 2-ft PFBC following the second-stage cyclone.[56] During test run 6/2, eight particulate measurements were made, indicating an average emission rate of 159 ng/J (0.37 lb/10^6 Btu). The results indicate that a third stage of control would be necessary to control particulate emissions to the currently regulated level of 13 ng/J (0.03 lb/10^6 Btu).

Granular bed and ceramic filters have been tested at the Exxon miniplant, the latter technique showing more encouraging results than the former, especially for removal of submicron particles. Operating difficulties were encountered with the granular bed filter although collection efficiency ranged between 90 to 95 percent. The ceramic filter was tested after the second-stage cyclone and demonstrated 99 percent efficiency with an average inlet particle size of 3.5 μm.[57]

2.3.1 Key Research on FBC Particulate Emissions

Research and development efforts to demonstrate the capability of various final particulate control devices applied to FBC systems are planned. Testing at various FBC demonstration facilities will include the application of conventional particulate control technology and novel devices. Table 5 lists some of the near-term programs that are planned.

GCA is conducting a study for EPA to identify and assess the suitability of conventional and novel control devices for collection of particulate emissions from fluidized-bed combustion systems. GCA will evaluate particle control technology for FBC by analogy to known criteria for judging suitability of control techniques for conventional combustion systems. Through literature search, new test data, and mathematical modeling, this characterization can be made. Some of the noval control techniques that will be considered for evaluation are:

TABLE 5. APPLICATION OF PARTICULATE CONTROL TO FBC DEMONSTRATION FACILITIES

Location	Developer	Sponsor	Type	Capacity	Status	Particulate control
Georgetown University Washington, D.C.	Foster-Wheeler Pope Evans & Robbins & Georgetown Univ.	DOE	AFBC	45,400 kg/hr steam	Start-up operations in progress	Fabric filter
Rivesville, W. Va.	Foster-Wheeler Pope Evans & Robbins	DOE	AFBC	88 MW_t	Intermittent operation because of technical problems	Hot side ESP
Alliance, Ohio	Babcock & Wilcox Company (U.S.)	EPRI	AFBC	6 MW_t	Operational	Fabric filter
Central Ohio Psychiatric Hospital Columbus, Ohio	Babcock & Wilcox Ltd. (England)	OHIO DOE	AFBC	27,250 kg/hr steam	Scheduled for startup Spring 1980	Fabric filter
Windsor, Conn.	Combustion Engineering	DOE	AFBC	1 MW_t	Operational	Fabric filter
Ferrysburg, Mich.	Johnson Boiler Co.	Private	AFBC	3 MW_t	Operational	Multitube cyclone
Great Lakes Naval Training Center, Ill.	Combustion Engineering	DOE	AFBC	22,700 kg/hr steam	Scheduled for startup mid 1981	Fabric filter
Linden, N.J.	Exxon Corp.	DOE	PFBC	2.2 MW_t	Operations suspended	cyclone
Woodridge, N.J.	Curtiss Wright	DOE	PFBC	13 MW_t	Under construction	Multitube cyclone

- electrified bed,
- electrostatically augmented filters,
- electrostatically augmented precipitators,
- electrostatically augmented scrubbers,
- ceramic fiber filters,
- granular bed filters,
- electrostatically enhanced moving granular bed,
- cyclonic-type dust collectors for high temperature and high pressure,
- particle-by-particle dry scrubber, and
- hot gas cleanup by glass entrainment processes.

Ceramic fiber and granular bed filters have been tested in FBC experimentation at the Exxon miniplant. The electrified bed concept for particulate control is being developed for FBC applications by Electrostatics, Inc., a subsidiary of EFB, Inc. and ERCO of Cambridge, Massachusetts. The other technologies are in an earlier stage of development.

Table 6 lists current high temperature/high pressure particulate control programs sponsored by EPA.[58] Results from these programs could be applicable to PFBC particulate control.

2.4 TRACE ELEMENT EMISSIONS TO AIR FROM FBC

A large body of recent work has shown that the smaller, "respirable" fly ash particles resulting from coal combustion may be considerably enriched in several toxic trace elements[59-64] as well as in inorganic and organic mutagenic species.[65-69] These data are of particular interest because particles this fine (< 2 μm) (1) are less efficiently captured by power plant control technologies, (2) have a long atmospheric residence time, and (3) are deposited deep in the lung and are not easily metabolized or otherwise removed. Some studies[70] have indicated that several trace elements (including Be, Cr, Pb, Tl, V, and Zn) present in fly ash particles are found preferentially concentrated on the particle surfaces. Because the surface of these particles is in intimate contact with biological tissue, this surface predominance could result in a greater tissue exposure or availability than that which would be expected if a homogeneous distribution of these trace elements in the aluminosilicate matrix of fly ash particles were assumed. Furthermore, it has been shown that biological tissue extracts trace metals much more efficiently from the small particles deposited in the deeper lung than from the larger particles deposited higher up in the respiratory system or from particles ingested.[71]

TABLE 6. HTHP PARTICULATE CONTROL PROGRAMS SPONSORED BY EPA

Collector type	Manufacturer/developer	Gas velocity (m/sec)	Pressure drop (kPa)	Overall mass collection efficiency (percent)	Status
Dry scrubber	Air Pollution Technology (APT)	20-60	2-7	96	Bench
Moving granular bed filter (MGB)	Combustion Power Company (CPC)	0.20-0.8	1-6	78	Commercial
Granular bed filter	Ducon	0.45	8	82	Commercial
Ceramic filter bag	Acurex	0.04-0.16	5	99	Pilot
ESP	Research Cottrell Denver Research Institute	1.0-2.0	0.2	NA	Bench
Cyclone	Exxon	NA	4	80	Commercial

NA = Not available.

The enrichment of trace elements in the finer fly ash particles emitted from coal combustion appears to be caused by the volatilization of the elements (or their compounds) in the combustion zone and their subsequent condensation or adsorption onto the suspended ash particles. This results in relatively higher concentrations of trace elements in/on the finer particles, which have greater surface-to-mass ratios. Models have been proposed to represent this concentration-particle size dependence in fly ash resulting from a volatilization-condensation mechanism.[72,73,74]

Because fluidized-bed combustion of coal is carried out at temperatures well below those of conventional combustion systems, it is possible that emissions of trace elements will differ. The presence of sorbent material in the bed adds another factor whose contribution to trace element emissions is unknown.

There are limited data available relevant to FBC trace element emissions. Preliminary experiments were conducted at ANL on a bench-scale 6-in. diameter PFBC in an attempt to evaluate the potential of FBC for reducing trace element emissions as compared to conventional coal combustion systems.[75] Trace element concentrations of solid materials in the inlet and outlet streams (plus Hg and F concentrations in flue gas) were measured. Mass balances were made for Hg, F, Be, Pb, As, Br, Co, Cr, Fe, K, La, Mn, Na, and Sc. Wet chemical techniques were used to measure Hg, Pb, Be and F; all others were determined by neutron activation analysis.

Results showed that losses of the relatively volatile elements Hg, F, Br, and As were decreased relative to conventional systems. Although concentrations of several elements (Co, La, Sb, and Sc) showed slight tendencies to increase with decreasing particle size of the ash, no enrichment of the magnitude seen in conventional combustion was observed. From these preliminary data, it was concluded that the lower operating temperatures typical of FBC processes apparently reduces the enrichment of some trace elements in/on finer flyash particles as compared to conventional systems.

To date, the most comprehensive sampling and analysis of FBC emissions has been the Level 1 environmental assessment conducted by Battelle Columbus Laboratories at the Exxon Miniplant PFBC.[76] Trace element analysis of particulate material entrained in flue gas was conducted on size-fractionated samples obtained using a Source Assessment Sampling System (SASS) train.[77] Both spark source mass spectrometry (SSMS) and atomic absorption spectrometry were used for elemental analysis.

Table 7 compares data from the Exxon Miniplant PFBC with those from analyses conducted on samples collected from the stack of a conventional power plant burning high-ash, low-surfur western coal, and reported by Fisher et al.[78] The trace elements were selected for comparison because they have been reported to be mutagenic, carcinogenic, or toxic. In addition, many of these elements have been reported to have pronounced (cd, Se, As, Sb, Pb, Ni) or more limited (Be, Mn) concentration trends on finer fly ash particles.

TABLE 7. ELEMENTAL CONCENTRATION OF SELECTED ELEMENTS IN SIZE-FRACTIONATED COAL FLY ASH PARTICLES FROM CONVENTIONAL AND FLUIDIZED-BED COMBUSTION SYSTEMS[a]

Test facility	Element	Analytical technique[b]	Concentrations in µg/g				Enrichment factor[d]
			Cut 1[c] 20 µm	Cut 2 6.3 µm	Cut 3 3.2 µm	Cut 4 2.2 µm	
Conventional power plant (High ash western low coal)	Cd	AAS	0.4	1.6	2.8	4.6	2.9
	Se	INAA	19.0	59.0	78.0	198.0	3.4
	As	INAA	13.7	56.0	87.0	132.0	2.4
	Sb	INAA	2.6	8.3	13.0	20.6	2.5
	Mo	INAA	9.1	28.0	40.0	50.0	1.8
	Pb	AAS	73.0	169.0	226.0	278.0	1.6
	Co	INAA	8.9	16.3	19.0	21.0	1.3
	Cu	AAS	56.0	89.0	107.0	137.0	1.5
	Be	AAS	6.3	8.5	9.5	10.3	1.2
	Ni	AAS	25.0	37.0	43.0	40.0	1.1
	Mn	AAS	209.0	231.0	273.0	309.0	1.3
			Cut 1 <3 µm		Cut 2 >3 µm		
Exxon Miniplant PFBC[18]	Cd[e]	AAS	2.5		1.4		0.6
	Se	AAS	17.0		22.0		1.3
	As	AAS	64.0		85.0		1.3
	Sb	AAS	3.3		5.3		1.6
	Mo	SSMS	10.0		5.0		0.5
	Pb	AAS	52.0		47.0		0.9
	Co	SSMS	30.0		30.0		1.0
	Cu	SSMS	70.0		40.0		0.6
	Be	AAS	11.0		14.0		1.3
	Ni	SSMS	400.0		200.0		0.5
	Mn	SSMS	200.0		200.0		1.0

[a]Data are from References 69 and 76.

[b]AAS = atomic absorption spectrometry
INAA = instrumental neutron activation analysis
SSMS = spark source mass spectrometry

[c]Cut points for conventional system data represent volume median diameters with associated goemetric standard deviations of approximately 1.8. Cut points for FBC data are nominal cut-off points of the SASS train cyclones.

[d]This factor = conc. cut point 3/conc. cut point 1 or (FBC) cut2/cut 1.

[e]FBC data are from Run 4 as reported in Reference 76.

Results of emissions analyses from the PFBC unit of the National Coal Board-Coal Utilization Research Laboratory at Leatherhead, England,[79,80] although also preliminary, tend to corroborate the Exxon data (see Table 8). These FBC data also indicate the potential of FBC processes to reduce concentrations of toxic trace elements on respirable particles. It should be mentioned, however, that the fine particles collected at Exxon demonstrated a positive mutagenic response in the Ames bioassay that was not observed for the particles > 3 μm. Unfortunately, Level 1 analyses are not sufficiently detailed to characterize the mutagenic agent(s). Therefore, the question of the role of volatilization-condensation as it relates to this mutagenic response is unresolved. These data, however are quite limited and preliminary, if suggestive, and no general conclusions should be drawn from them. They are the result of a limited number of sampling and analysis programs. Major issues need to be resolved in this area; this resolution can only come about through generation and analysis of more test data.

The major questions still unresolved are as follows:

- Is the deposition pattern of trace elements on emitted particles from FBC processes significantly different from that for conventional systems? If so, in what ways?
- What effect do operating conditions, that is, bed temperature, type of sorbent, type of coal, etc., have on trace element release?
- To what extent will increased particulate control efficiencies limit release of trace elements?
- Does release of trace elements differ between pressurized and atmospheric fluidized-bed units?

TABLE 8. COMPARISON OF SELECTED TRACE ELEMENT CONCENTRATIONS ($\mu g/m^3$) IN FLUE GAS EMISSIONS FROM THE EXXON MINIPLANT PFBC AND THE NCB-CURL LEATHERHEAD PFBC

Element[a]	Exxon miniplant[b]	Leatherhead[c]
Li	501.0	48.2
Be	16.0	1.9
B	237.0	455.0
Ti	7006.0	1607.0
V	186.0	103.0
Cr	366.0	897.0
Mn	306.0	395.0
Co	95.0	18.7
Ni	602.0	321.0
Cu	93.0	2678.0
Zn	130.0	5490.0
As	95.3	46.9
Se	34.0	593.0
Sb	6.7	28.1

[a]All elemental concentrations are measured by spark source mass spectrometry.

[b]Data are from Run 4 (see Reference 76).

[c]Data are from Test 6 (see Reference 80).

3.0 SOLID WASTE GENERATION FROM FBC

3.1 DESIGN/OPERATING CONDITIONS AFFECTING SOLID WASTE GENERATION FROM FBC

Solid residue from the fluidized-bed process consists of spent bed material (largely calcined and sulfated sorbent withdrawn from the combustor) and a mixture of fly ash, spent sorbent, and unburned carbon collected in the particulate control device.

The amount of solid waste generated is a function of the fuel and sorbent characteristics and the level of SO_2 control and particulate control. The major variables and their general affect on the amount of residue generated are listed in Table 9.

TABLE 9. OPERATING CONDITIONS AFFECTING QUANTITY OF SOLID WASTE GENERATED

Variable increased	Effect on quantity of waste
Ca/S molar feed ratio	increase
Sorbent reactivity	decrease
Gas phase residence time	decrease
Sorbent particle size	decrease
Percent SO_2 removal	increase
Percent coal sulfur	increase
Percent coal ash	increase

Different sorbents have varying calcium contents and calcium utilization rates. When a sorbent is chosen for a specific application, the calcium utilization rate can generally be increased by reducing the particle size. The design gas velocity and bed height can then be adjusted to give the optimum gas-solids contact time for a given particle size. The greater the gas phase residence time is, the greater the calcium utilization. When these parameters are established, the fuel feed rate and sulfur concentration and the level of control to be met determine the sorbent mass feed rate and amount of solid waste generated in the fluidized bed.

Figure 5 shows the relationship of the amount of land needed to dispose of FBC waste and the Ca/S molar feed ratio.[81] Five industrial boiler capacities are projected showing that the waste quantity from larger boilers is

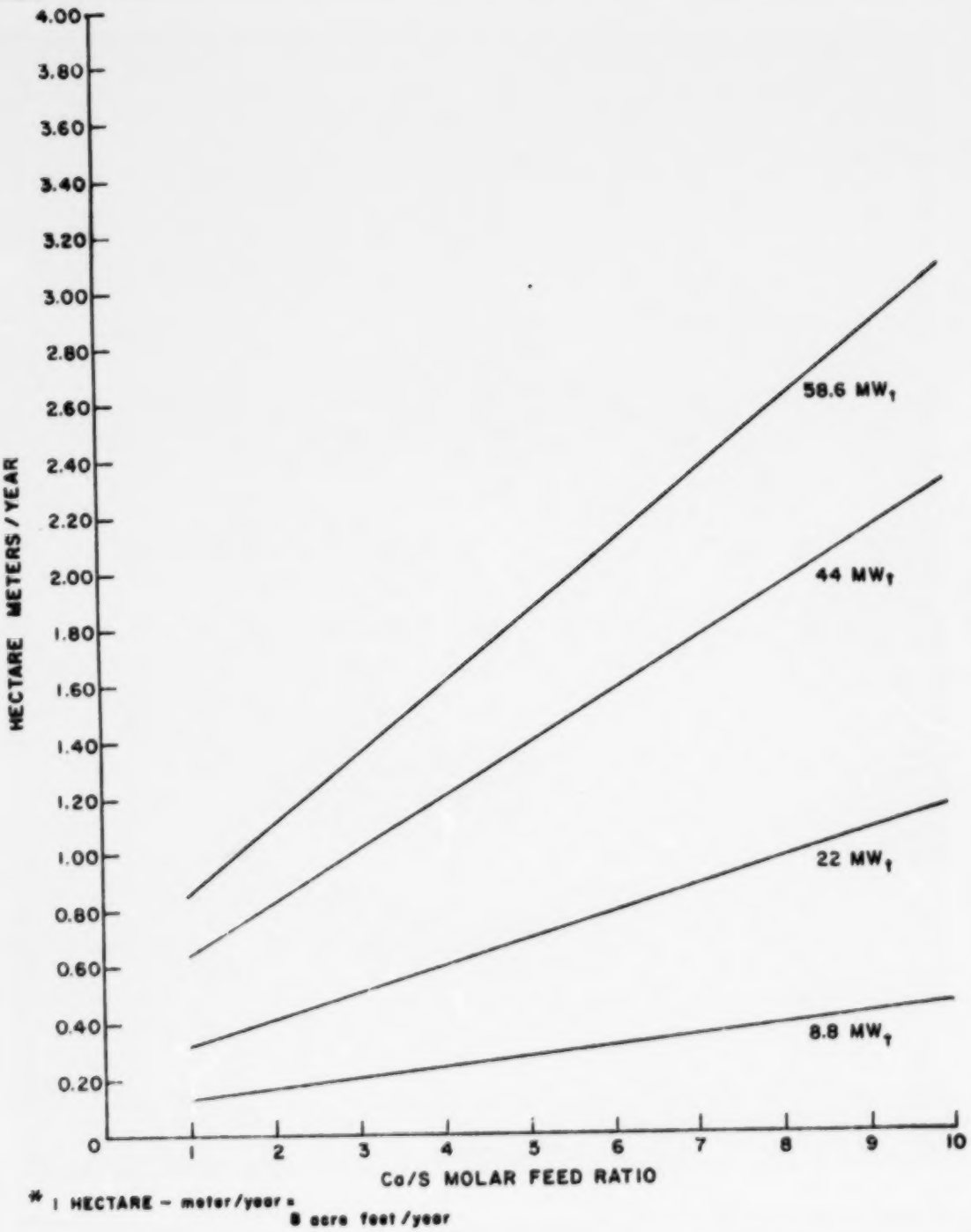

Figure 5. Land use requirements for disposal of solid waste.

more sensitive to Ca/S ratio than from smaller boilers. PFBC will most likely produce smaller quantities of solid waste than AFBC for equal SO_2 removal efficiency because PFBC can achieve the same level of control as AFBC with lower Ca/S ratios, thus a lower sorbent feed rate, and thus less solid waste. If sorbent regeneration becomes common, then differences in solid waste generation between AFBC and PFBC will be minimal.

In most cases, disposal of solid waste from FBC systems is expected to be performed by landfilling the material. The environmental impact of this method of disposal is under investigation. The primary sources of environmental degradation are the leachate formed by rainwater runoff and percolation after landfilling and the heat release from the material upon initial contact with water, because of hydration of the CaO in the waste.

3.2 EXPERIMENTATION ON SOLID WASTE FROM FBC

The environmental impact of disposal of solid waste from FBC is uncertain because of limited data on leachate generation and transport/transformation phenomena. Actual field cell testing of leachate quality and dispersion is just beginning.

The British Coal Utilization Research Administration (BCURA);[82] Pope, Evans, and Robbins;[83] Westinghouse;[84,85] and Ralph Stone and Company,[86] have conducted laboratory tests to investigate the properties of the leachate obtained from coal ash/limestone waste using distilled water. Their test results generally show the following common factors:

- high calcium content,
- high sulfate content,
- high total dissolved solids, produced by $CaSO_4$ going into solution, and
- high pH (10 to 12) produced by CaO content.

One of the most definitive evaluations of the potential contamination from FBC waste was performed by Westinghouse Research Laboratories.[87,88] Leachates were generated using distilled, deionized water in laboratory shake tests for a variety of FBC wastes; the resulting leachate concentrations were then compared with drinking water standards (National Interim Primary Drinking Water Regulations (NIPDWR-1975), and U.S. Public Health Services (USPHS) Drinking Standards).[89] The data are summarized in Table 10. This is a conservative approach and would tend to overestimate the impact because (1) the laboratory shake tests are designed to maximize the water extraction forces and (2) direct comparison with drinking water standards does not allow for any dilution of a leachate plume in the ground water. It is also important to note that drinking water standards are more stringent than leachate standards promulgated under Section 3001 of the Resource Conservation and Recovery Act (RCRA)[90] by a factor of 100, underscoring the conservative approach taken by Westinghouse.

TABLE 10. TRACE METAL ELEMENTS IN FBC RESIDUES AND LEACHATES[a]

Substances	Solid (wt)[b]		Leachate (mg/l)[c]		Drinking water standards
	Bed[d]	Carry-over[e]	Bed	Carry-over	(mg/l)[f]
Ag	<0.001	<0.001	<0.05	<0.05	0.05
Al	0 to 5	0 to >10	<2	0 to >2	
As	<0.03	<0.05	<0.05	<0.05	0.05
B	<0.03	0.01 to 0.1	0 to >5	0 to >5	
Ba			<1.0	<2.0[g]	1.0
Be	<0.003	<0.003	<0.02	<0.02	
Bi	<0.01	<0.01	<0.04	<0.04	
Ca	>10	>1	>500	>50	75
Cd	<0.006	<0.03	<0.01	<0.01	0.01
Co	<0.01	<0.01	<0.1	<0.1	
Cr	<0.02	<0.1	<0.05	<1.0[g]	0.05
Cu	<0.02	<0.02	<0.04	<0.1	1.0
Fe	0 to >10	0 to >10	<0.3	<0.3	0.3
Hg			<0.002	<0.002	0.002
Mg	0.1 to >10	0.1 to >1	<30	<250[g]	50
Mn	<0.05	<0.05	<0.05	<0.05	<0.05
Mo	<0.01	<0.01	<0.11	<5.0	
Na	0 to >0.1	0 to >0.1	0 to >10	0 to >100	
Ni	<0.01	<0.01	<0.04	<0.11	2.0
Pb	<0.01	<0.05	<0.05	<0.05	0.05
Sb	<0.01	<0.01	<0.01	<0.11	
Se			<0.01	<0.01	0.01
Si	0.1 to >10	>10	<2.0	0 to 30	
Sn	<0.005	<0.01	<1.0	<1.0	1.0
Sr	<0.1	<0.5	<10	0 to >10	
Ti			<1	<2	
V	<0.05	<0.05	<0.1	<1	
Zn	<0.03	<0.1	<1	<1	5.0
Zr	<0.02	<0.1	<1	<1	

[a]Based on data from currently available residues.

[b]Concentrations of trace elements in FBC solids are reported on a weight percent basis.

[c]Leachates were generated using distilled, deionized water in laboratory shake tests.[85]

[d]Spent bed material.

[e]Includes fly ash and elutriated sorbent.

[f]National Interim Primary Drinking Water Regulations. U.S. Public Health Drinking Water Standards and World Health Organization Potable Water Standards.

[g]Concentrations higher than the Drinking Water Standards resulted from leachates of <2 batches of carry-over fines among the >30 batches of FBC residues investigated.

The only components of FBC leachate that consistently exceeded the drinking water standards were the following:

- Ca,
- SO_4,
- pH, and
- total dissolved solids.

In addition, the following species exceeded the drinking water standards in less than two of the more than 30 FBC samples tested:

- Ba,
- Cr,
- Mg, and
- Cl.

Westinghouse[91] has concluded the following from their study.

- No water pollution is expected from the leaching of those trace-metal ions for which drinking water standards exist because the leachate itself meets drinking water standards.
- An insignificant amount of magnesium is leached out, even for dolomite sorbent.
- Sulfide may not be a problem for the once-through sorbent, because the sulfide concentration in the leachate is below detection limits.
- The total dissolved organics are below detection limits.
- Residual activity, reflected by heat release upon initial exposure to water, has been observed for once-through atmospheric pressure FBC systems and is judged as an environmental concern for direct disposal. The heat release is attributed to the large amount of calcium oxide present in the spent sorbent.
- Potential problems with the leachates are the high concentrations of calcium (Ca), sulfate (SO_4), pH, and total dissolved solids (TDS) that are above drinking water standards.

- The addition of 20 wt percent fly ash to the spent sorbent improves leachate quality. Thus, codisposal of spent sorbent and ash can reduce the adverse environmental impact.

- The environmental impact is reduced by room-temperature processing with water.

Table 11 gives a preliminary indication of the environmental impact of FBC solid waste disposal as observed by Westinghouse,[92] whose data indicate that FBC residue will not be a hazardous pollutant; however, it is still a candidate for the RCRA special waste category because of the volume of material that will be produced.

Ralph Stone and Company[93] evaluated fly ash and spent bed material and the leachates generated from these materials at two sites: the Exxon Miniplant (PFBC) and the Pope Evans and Robbins FBM (AFBC). The data are summarized in Table 12.[94-96] The results of the tests run by Ralph Stone illustrate the high pH of the leachate as well as the high total dissolved solids, calcium, and sulfate content for both AFBC and PFBC residues. These results are in accord with the Westinghouse conclusions. The trace element constituents for which drinking water standards are listed with the Westinghouse data are all less than ten times the standards.

3.3 RESOURCE CONSERVATION AND RECOVERY ACT (1976)[97] - IMPACT ON FBC SOLID WASTE DISPOSAL

The disposal of solid waste is governed by laws promulgated under the auspices of the 1976 Resource Conservation and Recovery Act (RCRA, PL 94-580). In response to RCRA, the EPA has proposed a regulatory program to manage and control the nation's hazardous waste from generation to disposal.[98] The program includes criteria for identification of hazardous waste (toxic, corrosive, ignitable and reactive), and rules and regulations for their management and control. When the EPA proposed the hazardous waste regulations, it set aside a unique category of special wastes - certain large volume wastes of which portions would be hazardous. The EPA plans to propose regulations governing special wastes in the early part of 1982. Until that time, the EPA has prepared special standards for each type of special waste. Although solid residues from coal-fired fluidized-bed combustion systems have not been regulated by the proposed program, they are a potential candidate for inclusion in the special wastes category that will include cement kiln dust, utility wastes (fly ash, bottom ash, scrubber sludge), phosphate mining and processing wastes, uranium mining wastes, other mining wastes, and oil and gas drilling muds and oil production brines.

FBC residue seems to be a potential candidate for the special waste category because it will be generated in large quantities when FBC technology is commercialized. Also, it contains chemical constituents similar to those found in utility wastes and cement kiln dust.

TABLE 11. PRELIMINARY INDICATIONS OF ENVIRONMENTAL IMPACT FROM THE FBC SOLID WASTE DISPOSAL[a]

Sample	Process	Sorbent type	Environmental parameters								
			Heat release[b,c] (spontaneous temp rise) 3 g/20 ml	Trace metal	Specific Conductance	Total[b] organic carbon	pH	Calcium	Sulfate	S=	Mg
Bed material	Pressurized FBC, once-through	Limestone	<0.2°C			<10 ppm					
Bed material	Pressurized FBC, once-through	Dolomite	<0.2°C			<10 ppm					
Bed material	Pressurized FBC, regenerative	Dolomite/Limestone	0 to 3°C			<10 ppm				f	
Bed material	Atmospheric FBC, once-through	Limestone	5 to 15°C			<10 ppm					
Carry-over material	Atmospheric FBC, once-through	Limestone	0 to 3°C	d		<30[e] ppm					
Carry-over material	Pressurized FBC, once-through	Limestone/Dolomite	<0.2°C			<10 ppm					d
Mixtures of bed and carry-over material (unprocessed)	Pressurized FBC, once-through	Dolomite/Limestone	<0.2°C			<10 ppm					
Processed composite from bed carry-over mixtures	Pressurized FBC, once-through	Dolomite/Limestone	<0.2°C			<10 ppm					
Gypsum	Natural		<0.2°C			<10 ppm					

Do not meet either the drinking water or gypsum leachate criteria.

Pass gypsum leachate criteria but not drinking water standards.

Pass both drinking water and gypsum leachate criteria.

[a]Based on data from currently available FBC residues

[b]No existing criteria

[c]Subjected to the specified procedures

[d]All except one pass drinking water standards

[e]All except one <10 ppm

[f]To be determined

TABLE 12. FBC SOLID RESIDUE AND LEACHATE CHARACTERISTICS (RALPH STONE & CO)[94-96]

Constituent*	NJFA		NJSBM		VFA		VSBM	
	solid	water soluble†	solid	water soluble	solid	water soluble	solid	water soluble
pH	-	9.3	-	12.2	-	12.2	-	12.9
Total dissolved	-	2,124	-	4,188	-	4212	-	-
COD	-	45.6	-	51.4	-	104.6	-	-
BOD	-	-	-	-	-	-	-	-
Chloride	-	N.D.††	-	N.D.	-	N.D.	-	22.03
Nitrate	-	27	-	26	-	2	-	7
Phosphate	-	4	-	N.D.	-	N.D.	-	N.D.
Sulfate	-	1,190	-	1,990	-	1,600	-	12,500
Aluminum	5,800	-	960	0.06	1,600	N.D.	1,860	N.D.
Arsenic	0.2	N.D.	< 0.1	-	< 0.1	-	0.3	-
Barium	60	-	120	-	200	-	120	-
Beryllium	-	-	-	N.D.	-	N.D.	-	N.D.
Boron	-	0.61	-	0.64	-	0.5	-	0.72
Cadmium	2.8	N.D.	4.0	N.D.	0.8	N.D.	2.4	0.3
Calcium	-	1,805	-	6,017	-	560	-	N.D.
Chromium	292	-	192	-	220	-	205	-
Copper	152	-	160	0.5	164	0.025	225	0.12
Iron	11,030	N.D.	1,030	N.D.	7,390	0.5	4,070	2.2
Lead	60	2.5	32	2.6	20	1.6	20	7.6
Magnesium	6,280	10	2,130	95	800	96	505	N.D.
Manganese	650	-	675	0.025	165	0.025	315	N.D.
Molybdenum	N.D.	N.D.	N.D	12	N.D.	10	N.D	7
Nickel	-	-	-	0.5	-	0.25	-	0.75
Potassium	7,200	24	5,600	32	8,600	33	19,600	-
Silver	-	N.D.	-	0.02	-	0.08	-	0.6
Sodium	85	23	72	89	112	143	192	-
Zinc	92	N.D.	92	N.D.	80	0.08	200	0.6

*All values are reported as mg constituent/kg residue.

†100 gms sample/250 mls distilled water.

††N.D. - not detected.

NJFA - New Jersey Fluxed/Sasco Miniplant

NJSBM - New Jersey Spent Bed Material/Sasco Miniplant

VFA - Virginia Fluxed/Pope Evans & Robbins, PER

VSBM - Virginia Spent Bed Material/Pope Evans & Robbins, PER

The EPA recommends that only the hazardous portions of special wastes comply with the proposed special standards. Section 3001 of the regulation provides the means for determining whether a waste is hazardous for the purpose of the Act. Whether portions of solid residues of FBC systems are hazardous will be determined by testing for toxicity - one of the characteristics that defines a hazardous waste. A waste is considered toxic under the authority of the Act if a chemical analysis of its water extract obtained in accordance with the Extraction Procedure (EP) reveals the presence of certain chemicals in concentrations that exceed one hundred times the drinking water standards. The contaminants and their maximum allowable concentrations are listed in Table 13.

TABLE 13. MAXIMUM ALLOWABLE CONCENTRATION OF CONTAMINANTS IN SOLID WASTE LEACHATE FOR DETERMINATION OF TOXICITY UNDER RCRA[90]

Contaminant	Maximum allowable extract level (mg/1)
Arsenic	5.0
Barium	100.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Selenium	1.0
Silver	5.0
Endrin	0.02
Lidane	0.4
Methoxychlor	10.0
Toxaphene	0.5
2,4-P	10.0
2,4-5-TP	1.0

This list is not final and may be revised by EPA through the rulemaking processs as information develops. Because the last six contaminants are synthetic organic compounds, it is very unlikely that they will be present in leachates from FBC wastes. The analysis, therefore, can be limited to the metal ions portion of the list. Wastes from several small-scale fluidized-bed combustion units have recently been tested by Westinghouse for EPA. None of the eight metals listed above exceeded the maximum allowable extract level.[98]

If these pollutants are measured in concentrations above the maximum allowable extract level, then the solid waste must be disposed of in compliance with the rules and regulations set forth in RCRA for toxic wastes. FBC residue will probably not be considered a candidate for corrosive, ignitable, or reactive categories under RCRA.

Current interpretations of RCRA indicate that "corrosive" applies to liquid wastes and not to leachate from solid waste; hence, despite its high pH, FBC waste would probably not be considered "corrosive." Furthermore, even though it does release heat when exposed to water, the reaction does not seem sufficient to meet current EPA criteria for "reactive" waste.

OSW is considering guidelines for radioactivity, controlled substances, mutagenic activity, bioaccumulation, analytic thresholds, and bioassay thresholds.

The following tests might have to be conducted to assess FBC residue for these characteristics.[99]

Radioactivity - Radium^{226} (solids)

Controlled substances - Benzene
- Carbon tetrachloride
- Cobalt salts
- Coumarin derivatives

Mutagenicity - Ames test
- Detection of gene mutation in mammalian cells in culture
- Mitotic recombination and gene conversion in yeast (Saccaromyces cerevisiae-D4)

Bioaccumulation - Reverse Phase Liquid Chromotography as in EPA-proposed guidelines.

Analytic thresholds - Drinking water - (in addition to those already listed in the proposed rules)

Radium^{226}
Fluoride
Nitrate
Calculated human LD_{50}

Bioassay threshold - Daphnia - 28-day static reproduction assay using Daphnia magna

Terrestial - Seed germination-radishes (Raphanus stativus)
- Seedling growth with wheat (Triticum aestivium) and soybean (Glycine max)

3.4 KEY RESEARCH ON SOLID WASTE GENERATION, DISPOSAL, AND UTILIZATION

Because of the large amount of solid waste generated, it is in the FBC opeator's best interest to reduce the quantity generated by whatever means are available. Currently feasible methods for lowering the volume of material are:

- using low sulfur coal,
- using a sorbent with high reactivity,
- increasing gas residence time, and
- decreasing sorbent particle size.

Methods currently under investigation and development are:

- other methods of improving calcium utilization, such as injection of sodium chloride or calcium chloride,
- spent stone regeneration,
- alternate synthetic sorbents that require less volume and have better regeneration qualities, and
- reactivation of spent stone by exposure to water.

The impact of disposing of solid waste must be studied in large scale (such as field cell testing) to adequately assess the feasibility of different disposal methods. John Minnick, under contract to the U.S. Department of Energy, is investigating the long-term environmental effect of disposing of FBC solid waste in open piles.[100] Preliminary indications are that after exposure to ambient moisture, a crust that is relatively impervious to subsequent precipitation forms over the pile. In this case, fugitive dust emissions from an open pile would be minimal after initial exposure to moisture.

FBC solid waste could be a useful byproduct. Because of the high amount of unused lime (CaO), uses as a cement supplement, agricultural additive, building material and road aggregate have all been explored and results are promising. As larger quantities of waste become available from operation of larger demonstration plants, a better assessment of the resource recovery possibilities can be made.

The Department of Energy (DOE) is funding a 5-year research program to identify and evaluate potential agriculatural applications for FBC solid wastes.[101] The study is being performed simultaneously in several states, all located in the eastern half of the United States, covering almost the entire range of crops grown in the Eastern United States. It includes both short- and long-term laboratory- and field-based evaluations. The waste is used as a replacement for lime to neutralize soil, as a source for trace and certain nutrient elements, and as a source for sulfur. The study

evaluates both the quality and quantity of crops produced from soil treated by waste material, as well as the crops' nutrient value as food for domestic animals.

A study to evaluate the physiological effects of food that was ultimately obtained from FBC waste-treated soils on people and animals has been proposed to DOE and EPA.[102] The study will monitor mineral balance and amino acids in human tissues, primarily human hairs, which tend to accumulate toxic materials. Some small animals will be evaluated over several reproductive cycles to determine long-term effects on offspring. The first stage of tests will start in October 1979, and the second stage is scheduled for 1980.

Several other studies have demonstrated that FBC solid residues, because of their unique chemical composition, possess cemetitious characteristics that, if exploited, can turn the waste into a very durable concrete-like mass. One such study investigated the potential for using FBC solid waste for road construction.[103] The results indicated that compressive strength of cemented waste exceeded the value recommended for heavy traffic highway construction over a wide range of compositions. Further, this compressive strength, which is indicative of the material durability and resistance to erosion, improved with time even after the cemented samples were subjected to the effect of freeze/thaw cycles. The study concluded that the exceptionally high strength of cemented FBC residue makes it suitable for applications requiring materials with low water permeability, such as in embankments, structural fills, and liners to control leaching from waste disposal dumps and logoons. The latter application is particularly important, because some clay-type liners that are being used in sanitary landfills have developed cracks allowing leachates to percolate into ground water aquifiers after several years of use.

Radian Corporation is conducting a study of the environmental effects of improperly disposing of fluidized-bed combustion residues. It includes an analysis of representative FBC residues and their interaction with natural environmental media and development of a method of ensuring environmental protection from the impacts of FBC wastes on a case-by-case basis. Residues from FBC and their interaction with six representative disposal media are being studied. Examination of leachate generation and attenuation for Ca, B, SO_4 and 17 other species was conducted by comparing volume-weighted averages of leachate concentrations with primary and secondary drinking water standards, Multimedia Environmental Goals (MEGs), and Quality Criteria for Water. With respect to drinking water standards, the parameters of greatest concern appear to be Cd, Mn, SO_4, and total dissolved solids. For the MEGs, Ca, Cd, Co, Ni, K, Ag, and Mn are all of concern. Only B is considered a special concern with respect to Quality Criteria for Water. The six disposal media were sandstone, shale, alluvium, glacial till, limestone, and interburden. The investigations include a multistep laboratory protocol for leachate generation from FBC wastes and subsequent attenuation of the leachate by the disposal media.

4.0 WATER EFFLUENTS FROM FBC

Although no supportive data are currently available, it is expected that water discharges from FBC units will be similar to effluents from conventionally fired boilers. The sources include boiler feedwater treatment wastes, boiler blowdown, cooling tower blowdown, fireside and waterside operational cleaning waste, and drainage from materials storage piles. A generalized diagram of FBC boiler water systems is shown in Figure 6.[104]

Table 16 summarizes the expected quantity and quality of wastewater streams from FBC technology in comparison to estimates for conventional coal fired power plants with flue gas desulfurization systems.[105] The major differences between the two technologies are expected to be runoff or leaching from materials storage and spent solids disposal sites and equipment cleaning wastes. Other streams should be similar because they involve components and operations which are equivalent for the two systems.

GCA/Technology Division will be conducting a Level 1 sampling and analysis program at the Georgetown University FBC facility early in 1980. Chemical and biological testing and analysis of liquid waste streams from Georgetown are included in the test matrix. Data generated by this program should provide a means of assessing the true character of water effluents from FBC. Priority pollutants will also be tested for the Effluent Guidelines Division of EPA.

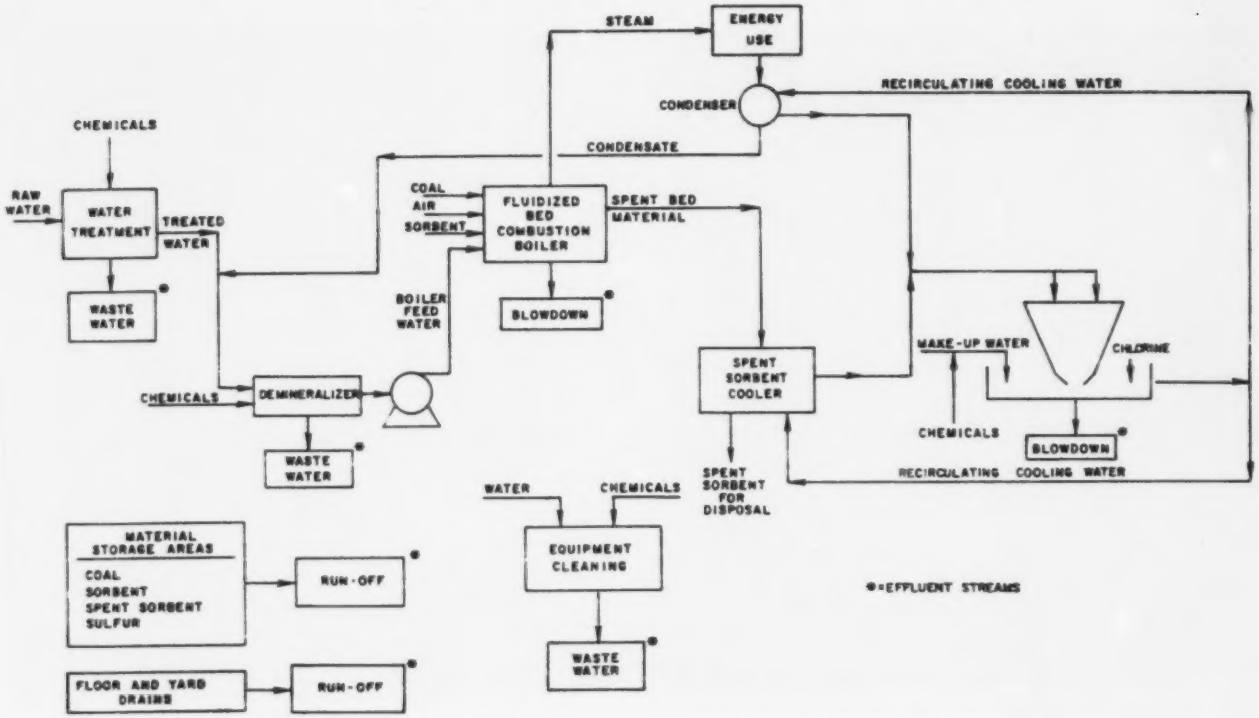

Figure 6. Typical flow diagram for a fluidized-bed combustion plant sources of wastewaters.

TABLE 14. COMPARISON OF WASTEWATERS FROM CONVENTIONAL AND FLUIDIZED-BED COMBUSTION SYSTEMS

Wastewater stream	Conventional combustion		Fluidized bed combustion	
	Quantity* (gpm)	Quality	Quantity	Quality
Cooling tower blowdown	4,300	Depends on raw water source and type of chemical treatment	Could be greater** by about 5 percent than conventional	Same as conventional
Once-through cooling system	500,000	Unchanged except for occasional chlorination	Same as** conventional	Same as conventional
Boiler blowdown	20	Depends on boiler pressure and type of chemical treatment	Close to the lower end of the conventional range	Same as conventional
Slurry from Flue gas desulfurization	2,200	Calcium sulfite, calcium sulfate, and unused sorbent	None	None
Water treatment waste	25	Suspended solids	Same as conventional	Same as conventional
Ash transport water	50	Suspended solids, alkaline pH, low content of heavy metals (i.e., Ni, Zn)	Expected to be higher than conventional	Suspended solids, higher pH and probably lower concentration of heavy metals

(continued)

TABLE 14 (continued)

Wastewater stream	Conventional combustion		Fluidized bed combustion	
	Quantity* (gpm)	Quality	Quantity	Quality
Runoff water from raw material storage areas and solid residue disposal site	†	Coal piles: low pH, dissolved solids, and trace metals. Sorbent piles: alkalinity, disolved solids, and trace metals. Ash disposal sites: acidity or alkalinity, trace elements.	Same as conventional for coal piles, but could be greater for sorbent piles and solid waste disposal sites due to higher Ca/S ratios.	Same as conventional for coal and sorbent storage piles. Leachate from spent solids disposal sites is expected to have high pH, dissolved solids, sulfate, and calcium.
Boiler cleaning waste	0.002	Copper, iron, alkaline or acidic pH	Lower than conventional	Same as conventional
Boiler fireside cleaning waste	0.03	Suspended solids	Less frequent than conventional	Suspended solids, high pH
Air preheater/ economizer cleaning waste	0.08	Suspended solids	More frequent than conventional	Suspended solids, high pH

*Flows are for 600 MW plant and are based on data collected by the Effluent Guidelines Division for utility power plant.

**Quantity may be reduced by improvements in AFBC efficiency and use of more efficient PFBC systems.

†Depends on local meteorological conditions.

5.0 MULTIMEDIA POLLUTANTS ASSOCIATED WITH FBC TECHNOLOGY

General pollutant categories that may be of concern in all FBC waste streams include organic species and radioactivity. This is true also for trace elements that have been discussed previously for all media. To date, organics have been characterized only on a limited basis, and virtually no experimentation has been performed to determine potential radioactive pollutants. Both will be pursued in future FBC testing.

5.1 ORGANIC POLLUTANTS IN FBC WASTE STREAMS

The products of coal combustion include aliphatic and aromatic organic compounds, aldehydes, ketones, and various small (less than three carbon) hydrocarbon compounds. Of these combustion products, one class has received special attention because it represents a serious potential for carcinogenic effects: the polynuclear aromatics (PNAS). The most widely studied of these is benzo(a)pyrene, which has clearly been established as a causative factor in skin and lung cancers among experimental animals.

Data available on emissions of organic compounds from fluidized-bed combustion (FBC) of coal are extremely limited. The most comprehensive analysis of FBC emissions to date was conducted by Battelle Columbus Laboratories on effluent and emission streams from the Exxon Miniplant PFBC.[106] One of the objectives of their analysis was to identify the major classes of organic compounds present in an effluent stream, provide an estimate of the concentration of these classes, and give some idea of the potential hazard posed by those classes present. The testing was done in conformance to EPA's phased approach to environmental assessment.[107] To "flag" organic classes for more specific (Level 2) analysis, the concentration values obtained in the initial screening (Level 1) are contrasted with Discharge Multimedia Environmental Goals (DMEG)[108] for the most toxic species within that category. Organic classes that exceed their worst-case DMEG values are thus identified for subsequent analysis.

In addition to the general investigation of classes or organic compounds, Battelle measured specific, selected PNA species in various Exxon effluent and emission stream samples. Among those assayed were benzo(a)pyrene and benzo(a)-anthracene. All those measured were present in extremely low concentrations in all streams sampled; all were orders of magnitude below their respective DMEG values, some were at or below analytical detection limits. Data from analysis of the flue gas stream for a selected run at Exxon are depicted in Table 15.[109]

TABLE 15. ORGANIC CHEMICAL ANALYSIS OF FLUE GAS AFTER DILUTION: POLYNUCLEAR AROMATIC MATERIALS, ng/m^3

Species	DMEG (air)	Observation exceeds DMEG
Anthracene/Phenanthrene	1.6×10^6	No
Methyl anthracenes	none	-
Fluoranthene	9.0×10^7	No
Pyrene	2.3×10^8	No
Methyl Pyrene/Fluoranthene	9.0×10^7	No
Benzo(c)phenanthrene	2.2×10^5	No
Chrysene/Benzo(a)anthracene	4.5×10^4	No
Benzo fluoranthenes	1.6×10^6	No
Benzo(a)pyrene	20	No

Polynuclear aromatic species were also measured by Battelle in output streams from the NCB-CURL PFBC facility at Leatherhead, England, as part of an EPA sampling and analysis program.[110] Levels of PNA and concentrations of specific compounds were similar to those at Exxon. All were orders of magnitude below their respective DMEG values. These low levels are in agreement with estimates that have been made for emission of these organic species from FBC facilities.[111]

5.1.1 Future Research and Data needs an Organic Emissions

Thus far no expansive, detailed data are available for organic emissions from any FBC facility. A Level 2 sampling and analysis program has been conducted recently at the Exxon Miniplant by GCA/Technology Division, and chemical analytical data will be available shortly.[112] There is an important need for such data if emissions or organic species from FBC of coal are to be quantified. So far, only a general analytical approach has been taken to quantify the organic content of emissions and effluents from FBC units. Future sampling and analysis will be aimed at quantifying specific organic pollutants.

5.2 RADIOACTIVE POLLUTANTS ASSOCIATED WITH FBC

5.2.1 Activities of the EPA Office of Radiation Programs

Radioactive contaminants, contained in emissions to the atmosphere or in solid waste residues, can be released to the environment from combustion of coal. Under the Clean Air Act Amendments of 1977, the Environmental Protection Agency is instructed to review all pertinent data to determine whether emission of radioactive pollutants into ambient air poses a threat to public

health. EPA is empowered to establish, implement, and enforce limitations, standards of performance, or other requirements sufficient to mitigate the potential hazards from such emissions. The EPA-Office of Radiation Programs (ORP) is conducting this review of all relevant, available information.

A major portion of ORP's efforts at this time involve compilation of data on radionuclide emissions from conventional coal combustion facilities. Data on radioactive emissions from non-nuclear systems are sparse and fragmented: data that are available are mostly derived through hypothetical models.[113-118] The reliability of some of the emissions estimates that have been proposed are questionable, and many assumptions have been made. Some actual air measurements have been taken.[119,120] Eisenbud and Petrow[121] conducted air sampling in New York City to assess the impact of radioactivity in atmospheric releases from plants burning fossil fuels. Martin et al.[122] measured uranium levels downwind from a 1400-MWe coal-fired power plant. Both studies concluded that the radionuclide releases measured and resulting population exposure doses calculated do not differ significantly from those for background concentration levels.

No comprehensive sampling, monitoring, or analysis has been conducted for radionuclide release from solid waste material resulting from coal combustion. Solid waste disposal sites may be a source of radioactive contamination because of the presence of radon gas derived from the uranium-238 and thorium-232 decay series. Fugitive radioactive particulate emissions should not be a problem at disposal sites because the waste material is generally landfilled or burned and backfilled with a cover layer of soil.

5.2.2 Radionuclide Characteristics from Coal Combustion

When combustion of coal occurs radionuclides enter the environment by one of two pathways: atmospheric releases, either as gases or contained in/on particulate matter that escapes final control devices, or as part of solid waste material. Studies have shown that there is a tendency for certain elements to be preferentially concentrated on fly ash particles small enough to escape control equipment. Uranium, lead, and polonium are believed to be concentrated in this manner.[123,124] FBC systems operate at lower combustion temperatures relative to conventional combustion systems (800° vs. 1400°C, approximately). In terms of emission characteristics FBC fly ash is more friable, that is, the lower operating temperatures of FBC combustors prevent the ash from fusing to its more vitrous form. It is reasonable to assume that the lower FBC combustion temperatures will alter the deposition of trace elements on size-fractionated particles. Some researchers believe that these lower temperatures will result in essentially all of the uranium and thorium isotopes being retained in the solid residue that is collected, as compared to that which escapes control devices.[125]

Radioactive elements not discharged into the atmosphere from coal combustion remain deposited on or in the solid residue that remains. This solid material includes bottom ash, slag, and particulate matter collected from control devices. For plants using fluidized-bed coal combustion technology, there is the added consideration of the contributions of spent sorbent

material to the volume and, to a lesser extent, to the radioactive content of the solid waste output of the plant. The large amounts of sorbent to be disposed of would tend to dilute the ash material in the disposal site, if co-disposal is practiced.

At present, most solid waste from coal-fired power plants is buried. In some cases, especially in the case of plants located in the western United States, waste is buried in discarded or abandoned mines. More commonly, solid waste residue is landfilled. If the material is buried sufficiently deep, there is virtually no chance of further airborne release of the remaining particulate radionuclides. Such is not the case with radon, which is gaseous. The solid waste material still contains all the elements in the uranium-238 and thorium-232 decay series, including radon-222 and radon-220. Radon emission from such disposal sites could pose a potential long-term hazard. This problem particularly involves radon-222 because radon-220 decays sufficiently quickly to eliminate any concern about its diffusion out of the landfill area. TRW has conducted some preliminary monitoring studies of coal ash disposal areas for radon isotopes for ORP. No radon emissions have been detected to date.[126]

Models that compare potential emissions of radon (together with other radionuclides) on a daily basis through atmospheric release, with the emanation of radon through diffusion from solid waste disposal areas have been generated. One model estimates that, on a daily basis, maximum release of radon from a disposal site is three orders of magnitude greater than the potential flue gas release if similar coals are considered.[127] Potential radioactive atmospheric release of other radionuclides is approximately 10 times less than that, even on a worst-case basis, which assumes selective concentration of certain elements.

Most researchers agree that for coal combustion processes in general, the radionuclide representing the greatest potential hazard is radon-222 when its source is the coal ash disposal area.[128,132] Potential exposure doses derived from other radionuclides in the ash pile, or from atmospheric release are comparatively insignificant. Once again, however, these conclusions are based on theoretical studies. No actual monitoring of solid waste disposal areas has been performed. ORP is currently initiating such studies for conventional systems. The differences in operation for FBC systems would contribute to altering the physical makeup or chemical characteristics of an FBC ash disposal pile. These physical and chemical differences for FBC ash will probably affect potential radon release from the disposal area, as will the incorporation of the spent sorbent material. However, experimentation must be conducted to characterize the effect of these differences on radon release.

An additional long-term problem resulting from disposal of this solid waste material in landfills is potential contamination of groundwater through leaching of radioactive material. Trace metals have been shown to migrate in groundwater from flyash disposal sites.[133] No comprehensive studies have been made to characterize radioactive isotopes for either conventional systems or FBC, so this potential problem cannot yet be quantified.

5.2.3 Radioassay of Samples from the Exxon Miniplant PFBC

The Exxon Miniplant is an experimental pressurized fluidized-bed combustor PFBC and sorbent regeneration system with a coal firing capacity of 1.8 MW (6.3×10^6 Btu/hr). GCA/Technology Division conducted Level 1 and Level 2 environmental assessment sampling and analysis programs at the Miniplant in May and June 1979. Level 1 samples were obtained with the regenerator in operation and the final particle control device was an ESP. Level 2 sampling was performed with no regeneration and final particulate control was implemented using a fabric filter.

Table 16 lists and describes samples obtained from the Level 1 and Level 2 sampling programs. Also indicated are those samples whose size or availability permitted radioanalysis to be performed.

Because the Miniplant is a small experimental unit, its relationship to a full-scale commercial plant needs to be considered. A commercial plant would consist of several modules with a total thermal input capacity near 1500 MW (5120×10^6 Btu/hr). Sorbent regeneration will probably not be used in first generation plants. When sorbent regeneration is used, the flue gases will be treated to recover sulfur.

To achieve economically competitive performance, flue gases from the combustor must be expanded through a gas turbine. Two options exist. The first option, similar to the Miniplant, is to use 2 or 3 stages of cyclones to reduce particulates to 22-65 ng/J (0.05-0.15 lb/10^6 Btu).* The flue gases would be expanded through a low pressure ratio heavy duty turbine to recover electricity. Final particulate control, similar to the fabric filter or ESP, would probably be needed to meet environmental standards. In this first case, inputs to the process would be coal and sorbent; solid waste would be spent bed material, cyclone catches, and fabric filter or ESP catch. Particulates emitted to the atmosphere would represent 20 percent or less (13 ng/J (0.03 lb/10^6 Btu) of the material entering the fabric filter or ESP. Flue gas flow rates would be similar to conventional combustion systems.

The second option would consist of better high temperature/high pressure particulate control. If the particulate concentration can be reduced to 1-20 mg/m^3 (equivalent to an emission rate below environmental standards) a higher performance gas turbine can be used to improve fuel to electricity efficiency. In this case a final low temperature 175-305°C (350-700°F) control device would not be used and emissions would consist of smaller quantities of particulates not collected at 800°C (1500°F) and 100 kPa (10 atm).

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*During the tests described in this report, particulate emissions were 60-80 ng/J (0.14-0.20 lb/10^6 Btu), and the concentration was in the 180-230 mg/m^3 range.

TABLE 16. IDENTIFICATION OF STREAMS SAMPLED AT THE EXXON MINIPLANT PFBC FOR RADIOANALYSIS

Stream No.	Stream description
Level 1	
1	Diluted combustor flue gas (ESP catch)[a]
2	Undiluted combustor flue gas
3	Cooled regenerator flue gas
4	High-pressure dilution air[a]
5	Regenerator cyclone catch[a]
6	Spent bed material[a]
7	Second cyclone catch[a]
8	Third cyclone catch[a]
9	Coal feed[a]
10	Sorbent feed[a]
Level 2	
1	Diluted combustor flue gas (fabric filter catch)[b]
2	Undiluted combustor flue gas
6	Spent bed material[a]
7	Second cyclone catch[a]
8	Third cyclone catch[a]
9	Coal feed[a]
10	Sorbent feed[a]

[a]Indicates that sample was available for radioanalysis.

[b]Final flue gas particulate was analyzed as ESP hopper ash for Level 1 and fabric filter catch for Level 2.

Results of the radioanalysis of Exxon Miniplant Level 1 and Level 2 samples have been reported[134] and are summarized in Table 17. ESP hopper ash (Level 1) and fabric filter catch (Level 2) were not available in sufficient quantity to permit analysis for thorium isotopes. The data show higher radioisotope concentrations in the relatively fine particles collected by the final control devices (stream 1). Cascade impactor measurements show that the particles entering the final control device are 95 percent by mass less than 4 m and 50 percent less than 2 μm. Secondary cyclone catch typically has a volume median diameter (determined by Coulter Counter) of 17 μm and the third cyclone catch typically has a median diameter of 4-6 μm.

TABLE 17. RESULTS OF RADIOANALYSIS OF EXXON MINIPLANT SAMPLES

Sample No. and Description	Activity in pCi/g(dry)±SD at 2 sigma confidence									
	^{238}U	^{234}U	^{235}U	^{228}Th	^{230}Th	^{232}Th	^{226}Ra	^{228}Ac	^{210}Pb	^{210}Po
Level 1 samples										
1 Particles in diluted flue gas – collected by ESP	4.7±0.8	4.8±0.8	<0.3	I[a]	I	I	5.2±1.3	3.6±0.5	1.4±0.3	10±0.8
5 Solid residue – regenerator cyclone	1.2±0.3	1.3±0.3	<0.4	<0.34	<0.34	<0.34	1.2±0.2	0.7±0.2	<6.0	<0.02
6 Combustion bed material	0.38±0.34	<0.2	<0.4	0.47±0.36	0.47±0.36	0.34±0.29	0.59±0.2	0.26±0.07	<8.0	0.041±0.014
7 Solid residue – second cyclone	<0.9	1.3±0.8	<2.0	0.23±0.21	<0.19	0.27±0.24	1.8±0.3	1.3±0.1	<10.0	0.15±0.02
8 Solid residue – third cyclone	1.1±1.0	2.0±0.8	0.96±0.87	1.2±0.5	1.4±0.6	1.3±0.5	4.3±1.0	2.8±0.5	<8.0	0.082±0.019
9 Coal feed	<0.3	0.12±0.11	<0.4	0.16±0.15	0.44±0.32	0.25±0.22	<0.3[b]	0.25±0.22[b]	<0.3[b]	<0.3[b]
10 Sorbent feed	<0.3	0.25±0.15	<0.2	<0.14	<0.42	<0.14	<0.3[b]	<0.14[b]	<0.3[b]	<0.3[b]
Level 2 samples										
1 Particles in diluted flue gas – collected by fabric filter	5.2±1.1	5.8±1.1	0.81±0.66	I	I	I	7.4±1.8	3.5±0.7	<4.0	7.1±1.0
6 Spent bed solids	0.68±0.24	0.66±0.21	<0.2	0.32±0.22	0.54±0.32	0.19±0.16	0.96±0.32	0.45±0.11	<8.0	0.11±0.01
7 Solid residue – second cyclone	2.3±0.5	2.6±0.5	<0.5	0.39±0.22	0.44±0.24	0.37±0.22	2.0±0.6	1.6±0.2	<5.0	0.035±0.014
8 Solid residue – third cyclone	2.3±0.5	2.2±0.4	<0.2	0.67±0.30	0.36±0.14	0.79±0.34	3.5±1.0	2.4±0.4	<6.0	0.25±0.03
9 Coal feed	0.14±0.3	0.13±0.2	<0.01	0.23±0.22	0.54±0.42	0.32±0.29	0.14±0.3[b]	0.32±0.29[b]	0.14±0.3[b]	0.14±0.3[b]
10 Sorbent feed	0.45±0.15	0.45±0.14	<0.2	<0.22	0.55±0.41	<0.22	0.45±0.15[b]	<0.22[b]	0.45±0.15[b]	0.45±0.15[b]

[a] I = indicates that there was insufficient sample available to run the analysis.

[b] = indicates that this analysis was not run; isotopes may be estimated assuming secular equilibrium.

Data listed in Table 18 illustrates the flow of individual isotopes through the systems sampled. In Level 1, spent combustion bed material is all regenerated or elutriated and collected by the cyclones so the flow rate is zero. Total amount of isotope in the system is equal to that in the coal plus the sorbent. For isotopes not quantified in the feed streams, secular equilibrium is assumed to exist and activity is assumed equal to that for the parent isotopes(^{238}U or ^{232}Th) that have been measured. Stream flow rates for final particle control devices are assumed equal to the flow rate for undiluted flue gas multiplied by the average dust loading measured for that stream (i.e., the final control devices operate at high collection efficiencies).

The data in Table 18 for Level 2 show that most of the radioisotopes leave the system in the spent combustor solids and the second cyclone catch. Level 1 data are similar except spent bed material leaves the system as part of the cyclone catch. Radioisotopes escaping the plant in the flue gases at Exxon or in a commercial plant would probably be 1 to 20 percent of the ESP or fabric filter catch.

TABLE 18. FATE OF INDIVIDUAL ISOPTIES WITHIN THE EXXON MINIPLANT PFBC DURING LEVEL 1 AND LEVEL 2 TEST

Sample No. and Description	Radioisotope flow rate, pCi/s										
	Solid flow rate g/s	^{238}U	^{234}U	^{235}U	^{228}Th	^{230}Th	^{232}Th	^{226}Ra	^{228}Ac	^{210}Pb	^{210}Po
Level 1											
9 Coal feed	21.4[b]	<6.4	2.6	<8.6	3.4	9.4	5.4	<6.4	5.4	<6.4	<6.4
10 Sorbent feed[a]	1.5[b]	<0.5	0.4	<0.3	<0.2	<0.6	<0.2	<0.5	<0.2	<0.5	<0.5
Total activity in	–	<6.9[f]	3.0	<8.9	3.4-3.6	9.4-10.0	5.4-5.6	<6.9[d]	5.4-5.6[d]	<6.9[d]	<6.9[d]
3 Cleaned regenerator offgas	0.0002[j]	0[g]	0[g]	0[g]	0[g]	0[g]	0[g]	0[g]	0[g]	0[g]	0[g]
5 Regenerator cyclone solids	0.2[h]	0.3	0.3	<0.1	<0.1	<0.1	<0.1	0.3	0.2	<1.6	<0.01
6 Spent combustion bed solids	0	0	0	0	0	0	0	0	0	0	0
7 Second cyclone solids	1.6[h]	<1.5	2.2	<3.3	0.4	<0.3	0.5	3.0	2.2	<16.7	0.3
8 Third cyclone solids	0.4[h]	0.5	0.9	0.4	0.5	0.6	0.6	1.9	1.2	<3.5	0.04
1 ESP hopper ash	0.042[j]	0.2	0.2	<0.01	NA[e]	NA	NA	0.2	0.15	0.06	0.4
Total activity out	–	1.0-2.5	3.6	0.4-3.7	0.9-1.0	0.6-1.0	1.1-1.2	5.5	3.8	<22	0.74
Level 2											
9 Coal feed	23.4[b]	3.3	3.0	<0.2	5.4	12.6	7.5	3.3	7.5	3.3	3.3
10 Sorbent feed[b]	2.9[b]	1.3	1.3	<0.6	<0.7	1.6	<0.7	1.3	<0.7	1.3	1.3
Total activity in	–	4.6	4.3	<0.8	5.4-6.1	14.2	7.5-8.2	4.6[d]	7.5-8.2[d]	4.6[d]	4.6[d]
6 Spent combustion bed solids	3.0[h]	2.0	2.0	<0.6	1.0	1.6	0.6	2.9	1.4	<24.0	0.3
7 Second cyclone solids	2.1[h]	4.9	5.5	<1.1	0.7	9.7	0.8	4.2	3.4	<10.6	0.1
8 Third cyclone solids	0.3[h]	0.8	0.8	<0.1	0.2	0.1	0.3	1.3	0.9	<2.2	0.1
1 Fabric filter catch	0.064[j]	0.3	0.4	0.05	NA	NA	NA	0.5	0.2	<0.3	0.5
Total activity out	–	8.0	8.7	<1.8	1.9	11.4	1.7	8.9	5.9	<37	0.73

[a]Sorbent feed rate was calculated from the Ca/S molar ratio of 1.29, 1.67% S coal and sorbent = 95% $CaCO_3$.

[b]Sorbent feed rate was calculated from the Ca/S molar ratio of 1.29, 1.84% S coal and sorbent = 57% $CaCO_3$.

[c]All isotope activity rates are in pCi/sec.

[d]These values assume secular equilibrium exists.

[e]NA = data are not available. There was insufficient sample size. Contributions to the total activity from these samples should be minimal.

[f]Totals were obtained by adding the contributions of coal and sorbent. Where one of these values is indicated as "less than" a range of possible values is given. Where other values are "less than", a maximum value is indicated.

[g]Not measured but believed to be near zero relative to the other streams because of the low solid flow rate.

[h]Measured by Exxon Research and Engineering during test program.

[i]Based on particulate concentrations measured by Exxon Research and Engineering and gas flow rates determined by GCA.

[j]Based on particulate concentrations measured by Exxon Research and Engineering and gas flow rates determined by GCA.

6.0 BIOASSAY TESTING OF FBC EMISSIONS

6.1 INTRODUCTION

Conclusive results from bioassay testing of FBC emission/effluent streams are not yet available because of limited testing, different and in some cases imcomparable analysis methods, and continually changing protocols and procedures for performing bioassays. The data that are available generally indicate positive health effects assay response to airborne particulates and positive ecological effects response to coal, spent solids, and collected fly ash material. In general, based on limited comparative results, health and ecological effects from FBC waste streams are not expected to be greater than those resulting from conventional combustion. In fact, early test results indicate that FBC fly ash may have less potentially adverse impact than fly ash from conventional systems.

The phased approach to environmental assessment developed by EPA's Industrial and Environmental Research Laboratory (IERL) has provided the impetus for much of the current and future work to be performed to characterize the potential health and ecological effects associated with effluent or emission streams from FBC processes.[136] The Level 1 bioassay test regimen was created as an initial screening program to give some indication of potential environmental hazards which might be associated with the various emission streams generated by industrial processes. Problem streams identified by Level 1 testing receive more detailed, intensive study under Levels 2 and 3. Level 1 bioassays are divided into Health Effects Tests and Ecological Effects Tests; these assays are listed in Table 19.

FBC bioassay test data are available from limited sources. Among these are results from the Exxon Miniplant PFBC[139] and the AFBC bench-top unit at Morgantown Energy Technology Center (METC).[140-142] The Exxon data encompass a comprehensive Level 1 bioassay analysis, whereas limited analyses have been performed on METC samples. Some preliminary studies on FBC samples have also been performed by researchers at Argonne and Oak Ridge National Laboratories as part of overall programs to characterize biological or other responses of effluents from alternate energy technologies.[143,144] These studies have been specific--only limited numbers and types of samples have been tested. Available data are discussed below.

Because of the limited data on biological activity of FBC samples, few conclusions regarding potential health or ecological effects of FBC process can be drawn. However, some test results do indicate a response that differs from results obtained through testing of comparable samples from conventional combustion systems. Also, because data are scarce, few meaningful correlations

TABLE 19. BIOASSAYS SPECIFIED FOR LEVEL 1 ENVIRONMENTAL ASSESSMENT

Original tests specified[137]	Recent changes[138]
Health Effects Tests	
Ames mutagenicity assay employing *Salmonella typhimurium*	Strain 1538 is not required.
Rabbit alveolar macrophage (RAM) cytotoxicity assay. Cytotoxicity assay using WI-38 human lung fibroblasts.	WI-38 assay has been dropped and a cytotoxicity assay using Chinese hamster ovary (CHO) cells is now recommended.
Rodent acute toxicity test.	
Ecological Effects Tests	
Freshwater algal assay using *Selenastrum capricornutum*	
Static acute toxicity fresh water tests using:	*Daphnia magna* has been substituted for *Daphnia pulex*
Fathead minnow (*Pimephales promelas*) and	
Daphnids (*Daphnia pulex*)	
Stress ethylene plant response test	Both terrestrial assays have been dropped (plant response and soil microcosm). Currently under consideration are Seed Germination/ Seedling Growth tests; Soil Respiration/Nitrogen Fixation tests; and Insect bioassays. None have been specified as of yet.
Soil microcosm test	

between bioassay results and corresponding chemical pollutant characteristics have been made.

6.2 FBC BIOASSAY RESULTS

The most comprehensive biological testing of FBC process and effluent stream samples to date has been the analyses performed on the Exxon Miniplant PFBC.[139] Streams sampled and analyzed at the Exxon Miniplant included: coal feed, sorbent feed, spent bed material, fly ash (second cyclone catch), particulate matter entrained in flue gas (size fractionated samples), flue gas, and scrubber slurry. Bioassay results for these samples are presented in Table 20. In health effects testing, positive responses were found for fine and coarse particles collected in the SASS train. Positive responses were observed with coal and spent bed material in ecological effects testing.

In all of the bioassays of Exxon samples where leachates were tested, the length of storage of the solid samples and their respective leachates may have affected sample composition. In some instances, up to 3 months may have elapsed between leachate generation and biological testing. In view of the sample conditions, bioassay test results from these leachates must be regarded as questionable.

Available data from other investigators on FBC samples are summarized in Table 21. Most data are sketchy and have been obtained from "internal" documents, i.e., progress reports, etc., consequently, their value may be limited.

Comparisons between FBC bioassay data are difficult because testing procedures are not always comparable. In some cases, raw data alone are available, and descriptions of experimental procedures followed are lacking. The remaining discussion of FBC bioassay data is limited to those assay systems currently specified for Level 1 testing; thus data from the rodent toxicity test (all results were negative in any case) and the two terrestrial assays are not included.

Ames results were negative for Exxon coal samples; one concentration was assayed from a METC test run and it was likewise negative. No cytotoxicity testing was run for Exxon, but METC samples showed appreciable toxicity to the BALB/C3T3 mouse fibroblast cells (EC_{50}=13.4 µg/ml). This cell line is not included in Level 1, so comparative results from Exxon are not available. In general, it must be assumed that toxicity demonstrated for samples of coal will be equivalent for FBC and conventional systems.

Exxon coal leachate produced a pronounced positive response in the algal assay; positive response was also observed in the freshwater test protocols. Similar to health effects test results, these positive results cannot be assumed to be unique for FBC processes because of the limited data base.

As shown in Table 20, Exxon sorbent leachate samples were negative in all tests with the exception of some slight toxic response to Daphnia. No corroborative or other data are available.

TABLE 20. EXXON MINIPLANT BIOASSAY RESULTS[139]

	Coal	Sorbent	Spent bed	SASS fine particulate[a]	SASS coarse particulate[b]	Flue gas	Fly ash[c]	Scrubber slurry
Health Effects Tests								
Ames	-	-	-	+	+	N	-	N
Cytotoxicity (RAM)	N	N	-	+	-	N	-	N
Rodent acute toxicity[d]	-	N	-	N	N	N	-	N
Ecological Effects Tests								
Algal growth	+[e]	-[e]	+[e]	N	N	N	-	+
Static acute toxicity - fish	+[e]	+[e]	+[e]	N	N	N	-	+
Static acute toxicity - *Daphnia*[f]	+[e]	+/-[e]	+[e]	N	N	N	+/-[e]	+
Stress ethylene[d]	N	N	N	N	N	-	N	N
Soil microcosm[d]	+/-	-	+	N	N	N	+	-

Key:

+ = toxic or mutagenic response.

+/- = equivocal response.

- = no toxic or mutagenic response.

N = test not run.

[a]Sample is particles $\leq$ 3 μm diameter collected with the SASS train from the flue gas stream downstream of the dust collector.

[b]Same as a but particles $\geq$ 3 μm.

[c]Fly ash is defined here as the second FBC cyclone dust collector catch.

[d]Assay procedure dropped from Level 1.

[e]Leachate of the sample tested.

[f]Run with *Daphnia pulex*; *Daphnia magna* now specified for Level 1.

TABLE 21. SUMMARY OF OTHER AVAILABLE FBC BIOASSAY DATA

Samples tested	FBC unit	Endpoint measured	Assay system(s)	Results	Comments	Reference
Coal Spent bed Fly ash SASS fine particulate	METC	All samples tested for mutagenicity and cytotoxicity	Ames Mouse fibroblast cell line	All samples negative in the Ames test. All samples exhibited some cytotoxicity to this cell line.	Very low sample conc. tested. Results must be regarded as inconclusive. Cell line used is not recommended for Level 1. Comparison between these results and Exxon data difficult.	142
Bag-filtered fly ash	METC	Mutagenicity	Ames	Methylene chloride extract was mutagenic	Illustrates difference in Ames response between FBC and conventional ash.	140
Size-fractionated particles		Mutagenicity	Ames	All size-fractionated samples - Ames negative.	Run as above	
		Cytotoxicity	RAM	Particles $\geq$ 3 m - negative, $\leq$ 3 m - positive	Corroborates Exxon data	141
Fly ash	Argonne	Mutagenicity	Ames	Fly ash and its organic extracts Ames positive. Greater response than Exxon samples.	Available data very limited. Argonne no longer active in this area. Differences unresolved.	143
"Respirable" particulate	Unspecified	Cytotoxicity	RAM	Toxicity so low, no EC_{50} calculated.	Data not available — internal reports only.	147
Leachate of spent bed	Unspecified	Acute and chronic aquatic toxicity	*Daphnia magna*	Moderate acute toxicity	Data or protocols not available — internal documents.	144
XAD-extract		Mutagenicity	Ames	Ames negative/		
Spent bed solids-		Mutagenicity	Ames	all samples		

Potential health or environmental effects associated with spent bed material are of special concern because these materials are unique to FBC coal processes. Spent bed solids were tested for mutagenicity for Exxon samples, METC samples and at Oak Ridge. All samples were Ames negative. RAM test results show no toxicity for Exxon samples. METC samples were cytotoxic using the mouse fibroblast cell line but data reported are internally inconsistent. EC_{50} values reported range from 21 to 808 µg for similar samples.

The positive response demonstrated by spent bed material leachate could be of concern because solid waste from FBC systems is expected to be landfilled. Exxon data show that spent bed leachate exhibited positive responses in the algal growth assay as well as in the static acute tests using fathead minnow or Daphnia pulex; these results have been corroborated by Oak Ridge investigators who have demonstrated a moderate positive response to Daphnia magna from leachate samples.

Biological response of fly ash particles from FBC have received the most investigative attention of any samples to date. Exxon fly ash samples (second cyclone catch) showed no mutagenic activity. Fly ash samples obtained from the METC FBC, and analyzed by Battelle, were also negative. The METC tests were run only at low concentrations of samples, however, so absolute conclusions about this negative result cannot be drawn. Preliminary results of work at ANL had indicated that fly ash samples obtained from their bench model 6-inch FBC were highly mutagenic to three of the five Ames Salmonella strains. Discussions with Argonne personnel revealed their belief that differences in sampling conditions (temperature, for instance) could affect mutagenic response of fly ash samples.[145] Argonne has discontinued this line of investigation, so these differences remain unresolved.

Researchers at the Inhalation Toxicology Research Institute (ITRI), part of the Lovelace Biomedical and Environmental Research Institute in Albuquerque, New Mexico, have obtained interesting results using extracts of fly ash samples from the METC FBC while it was burning various types of coal under various operating conditions.[140,141] Samples evaluated included bulk fly ash samples trapped in bag filters as well as size-fractionated particle samples collected by cascade impactors in the stack breech.

The purpose of the investigation was to evaluate mutagenicity of the collected FBC samples as an initial screen in a multi-component testing program. Also of interest was the aim of establishing whether FBC fly ash extract exhibited mutagenic response that differed from that reported for ash from conventional coal combustion systems. Chrisp et al.[146] have presented evidence that cyclohexane, saline, or horse serum extracts of size-fractionated fly ash particles from conventional systems were mutagenic using the Ames system.

Pilot studies with FBC fly ash by Clark et al.[140] had indicated that it was necessary to extract five times the amount of FBC bag filtered fly ash as compared to conventional ash to detect any mutagenic response. In addition these studies showed that cyclohexane extracts were negative, whereas methylene chloride extracts of the same ash were positive.

These earlier observations were confirmed in this study using fly ash samples collected in the bag filter from burning of Montana Rosebud coal. Identical samples of Montana Rosebud fly ash were extracted with equal volumes of methylene chloride and cyclohexane. As noted in Table 22, the methylene chloride extracts produced significant mutagenic responses in strains TA-100, 1537, 1538, and 98, whereas cyclohexane extracts were not mutagenic at any of the doses tests. Re-extraction of the cyclohexane-extracted ash with methylene chloride reproduced the mutagenic response.

TABLE 22. MUTAGENICITY OF METHYLENE CHLORIDE AND CYCLOHEXANE EXTRACTS OF MONTANA ROSEBUD FLY ASH (BAGFILTER)[140]

Sample	Fly ash extracted per plate (mg)	Number of revertants (without/with S-9[a])				
		Salmonella typhimurium strain				
		TA 1353	TA 100	TA 1537	TA 1538	TA 98
Spontaneous Revertants (Control)	-	9/7	152/141	10/13	27/40	9/37
Montana Rosebud[b] (methylene chloride extract)	500	-	319/433[c]	-	83/485	-
	250	-	269/391	-	81/142	-
	125	8/13	216/304	45/36	91/87	96/82
Montana Rosebud[b] (cyclohexane extract)	500	-	112/131	-	12/29	-
	250	-	107/117	-	17/36	-
	125	7/5	122/117	8/8	11/25	12/27
Montana Rosebud[b] (methylene chloride extraction after cyclohexane extraction)	500	-	316/626	-	98/526	-
	250	-	269/435	-	125/218	-
	125	7/7	152/259	52/23	70/55	105/116

[a]S-9 = rat liver homogenate, source of metabolizing enzymes.

[b]Collected in bag filter of METC FBC.

[c]Underlined values indicate mutagenic response in this test system.

Horse serum or saline extracts of similar samples failed to produce a mutagenic response. This is in direct contrast to the results reported for conventional combustion fly ash samples by Chrisp et al.

Fly ash samples collected in the bag filter from combustion of Western Kentucky coal and Texas lignite were extracted with cyclohexane or methylene chloride in a manner similar to that for Montana Rosebud. Methylene chloride extracts of Texas lignite fly ash demonstrated mutagenic activity while those from Western Kentucky coal did not. Cyclohexane extracts were negative for all samples.

Of particular interest is that some samples of Montana Rosebud fly ash collected were not mutagenic even when large quantities were extracted. It was observed that the operating temperature of the fluidized bed varied on the three sampling runs during which Montana Rosebud was burned and ash collected. It was suggested that since mutagenicity varied with different samples (collected in a similar manner) from the same coal type, it is possible that operating conditions of the combustor might influence mutagenic activity of the resultant ash.

Although evaluation of fly ash retained in the FBC by bag filters is interesting, the mutagenic activity of the emissions leaving the stack is more relevant to health or environmental concerns. Addition of a high-volume sampling system in the stack at METC permitted collection and evaluation of size-fractionated fly ash samples more representative of what might be discharged to the atmosphere. One set of such samples was obtained from combustion of Western Kentucky coal. Extracts representing 125 mg of such flyash were tested from each of the six stages of the impactor. All samples were negative, as shown in Table 23. Bag-filtered fly ash extracts from the combustion of the same coal were rechecked at the same time. These samples were also negative.

TABLE 23. MUTAGENICITY OF SIZE-SELECTED WESTERN KENTUCKY FBC FLY ASH EXTRACTS[a] [140]

High volume Sierra impactor stage number	Effective Cut-off Diameter (μg)	Approximate g Total hydrocarbon per plate[b]	TA-1538 Number of revertants	
			Without S-9[c]	With S-9[c]
1	8.27	46	18	25
2	3.59	89	12	28
3	2.25	26	15	29
4	1.15	32	15	31
5	0.67	80	19	32
6	< 0.67	86	14	30
Spontaneous revertants (control)	-	-	15	48

[a] Fly ash extracted with methylene chloride.

[b] Represents extraction of 125 mg fly ash.

[c] S-9 = rat liver homogenate, source of metabolizing enzymes

Although it may be argued that the observed mutagenicity of these FBC effluent samples cannot be directly compared to that of ash from conventional coal-fired systems, because of differences in coal types, sampling procedures, etc., this work has discovered some obvious differences.

- It has been reported that cyclohexane extracts of approximately 8 mg of conventional fly ash were mutagenic in the Ames test; cyclohexane extracts of up to 500 mg of FBC fly ash were reported to be negative in this work.

- Extraction of FBC fly ash with horse serum or saline (used because of their similarity to alveolar and physiological fluids) did not result in a mutagenic response, as did extraction of conventional ash reported by Chrisp et al. Methylene chloride did extract mutagenic components from FBC samples.

Based on these differences, it appears that the quantity or solubility of mutagenic components is different in the two ash types.

As reported, there are some data that suggest that combustor operating conditions may influence ultimate mutagenic response of the resultant flyash streams. Further, more specific studies would appear to be needed to better characterize and determine to what extent this correlation may exist.

These results may also be compared to the Exxon data where fly ash was Ames-negative. Size-fractionated particulate samples collected in the SASS train also differ in Ames response to those collected by cascade impactor and assayed by Clark et al. Particles collected in the SASS train at Exxon were Ames-positive while all size-fractionated samples analyzed by Clark et al. were Ames-negative. Resolution of these differences is not possible at the present time but it will be important to resolve such apparent inconsistencies in future testing.

Exxon fly ash was assayed using the RAM test; no toxicity was observed. Size-fractionated samples differed in their cytotoxic response; this difference paralleled that for mutagenicity. Fine particles (< 3 μm) collected by the SASS train were moderately toxic in the RAM test, whereas coarse particles (≥ 3 μm) were negative. These results were corroborated by workers at ITRI who showed particles collected that were ≥ 3 μm from the METC FBC were toxic to RAM using an assay system analagous to that for Level 1. Particles ≥ 3 μm were negative. Cytotoxicity assay using RAM were run on "respirable" particles by Northrop Services, Inc., for HERL.[147] All results were negative although no data were presented.

Leachate from fly ash that would be disposed of in a landfill area would be a concern similar to leaching of material from spent sorbent. Limited toxicologic data are available for flyash leachate; Exxon data reveal no toxic response to algae or fathead minnow. The leachate showed some toxicity towards Daphnia.

6.3 FUTURE RESEARCH AND DATA NEEDS

As mentioned previously, no firm conclusions may be drawn regarding health or ecological effects of FBC based on the limited data available. There is an obvious need for comprehensive sampling and analysis of FBC effluents on a broader scale using comparable analytic or assay techniques. Among some of the more specific areas of research that need to be accomplished are:

- characterization of the identity and/or chemical activity of mutagenic components of FBC fly ash and size-fractionated particles,
- elucidation of the differences in the mechanism of deposition of mutagenic components (both organic and inorganic species) on FBC versus conventional particles,
- determination of the effects of combustor operating conditions on this deposition and/or on the subsequent mutagenic response of these particles,
- determination of the effects of sampling temperature or other sampling conditions on mutagenic response, and
- more comprehensive investigations into the biological activity of leachates from FBC solid waste materials.

7.0 SUMMARY AND CONCLUSIONS

Comprehensive emissions data from FBC processes are limited. Those data which are available have, in general, been obtained through sampling and analysis of effluent and emissions streams from bench-top or other pilot-scale units under controlled operating conditions. Numerous models that attempt to predict FBC emission characteristics and the impact of these emissions on health and the environment have been generated. Using these data, any conclusions drawn regarding FBC environmental impacts must be considered preliminary and should be verified in future testing.

Data that are available have indicated that FBC technology is a viable alternative to conventional coal combustion. Adverse impacts on health or the environment appear to be minimal and are, at worst, no different from impacts associated with conventional coal combustion systems. Future testing and emissions analysis are needed to further quantify and assess these impacts.

7.1 ENVIRONMENTAL IMPACT OF FBC SYSTEMS

At present, impacts of FBC may be summarized as follows.

Air: a major attribute of FBC processes is the ability to minimize emissions of SO_2 and NO_x typical of coal combustion. Coal is burned in FBC in the presence of sorbent for sulfur removal (usually limestone); percentage SO_2 removal is directly dependent on the ratio of calcium in the limestone to the sulfur in the coal. Experimental data indicate that AFBC can achieve 90 percent SO_2 reduction with Ca/S ratios as low as 2.6; PFBC can attain this reduction level with Ca/S of about 1.0. Typically, for this level of reduction, a Ca/S ratio of 3.0-3.5 is required for AFBC, and from 1.0-2.0 for PFBC.

Low NO_x emissions are inherent to FBC processes although the kinetics of NO_x reduction are not well understood. Data indicate that PFBC systems generally produce lower NO_x emissions than AFBC. Emissions as low as 22 ng/J (0.05 lb/10^6 Btu) have been achieved using FBC technology. NO_x emissions have typically been in the range of 86-215 ng/J (0.2-0.5 lb/10^6 Btu) in larger experimental units.

Particulate emissions from FBC may differ from emissions from conventional combustors in quantity and chemical makeup because of differences in operating conditions and contributions from elutriated sorbent material. Based on available experimental results and engineering considerations, it is projected that the application of conventional particulate control technology will limit releases to acceptable levels. Environmental impacts associated

with particulate material will mainly be those produced by disposal of the collected particles as solid waste. Impacts from the particles that escape control equipment can be assumed to be no worse than those associated with particles emitted from conventional systems.

Land/Surface or Ground water: The major environmental impact of FBC processes is expected to be produced by the solid waste material generated. Such solid residue consists of spent bed material and a mixture of fly ash collected in particulate control devices. Handling and disposal options need to be further defined and evaluated. FBC solid residue possesses the potential for heat release upon contact with water, has high pH, and has a high amounts of dissolved solids. Leaching of trace metals from coal ash and limestone residue needs more detailed quantification.

Based on data currently available, no insurmountable pollution problems for handling or disposal of FBC solid waste are anticipated. Further investigation into disposal options and chemical characterization of this waste, including leachate generation studies, are currently underway by several investigators. Preliminary results indicate that although FBC solid waste material will be produced in large volume, the residue does not appear "hazardous" as defined under RCRA Section 3001.

Effluents from FBC facilities are expected to be similar to those for conventional systems. Difference could be seen in rainwater runoff/leachate from sorbent storage piles, and equipment cleaning wastes.

Multimedia: A large body of recent work has shown that particles <2 μm diameter, the so-called "respirable" particles, are considerably enriched in several toxic trace elements following their emission during coal combustion. It has been postulated that FBC processes, because their operation at lower combustion temperatures, might not exhibit such a concentration-size relationship if it were a result of a volatilization-condensation mechanism. Preliminary results seem to support this hypothesis because concentration of elements on size-fractionated particles from FBC exhibited size-dependence to a lesser extent than that seen for conventional systems. More thorough, detailed investigation is needed in this area.

Radioactive contaminants, contained in emissions to the atmosphere or in solid waste residues, can be released to the environment from combustion of coal. Minimal data are available for radioactive emissions from conventional coal combustion processes; in support of EPA-Office of Radiation Programs activities, analyses were conducted on Level 1 and Level 2 Exxon Miniplant PFBC samples for selected radioisotopes. Data indicate that radioactive species in Exxon samples would be mostly contained in spent bed solids or as part of the cyclone catch of flue gas particles.

Quantitation of health and ecological effects of FBC effluent and emission streams will rely on the bioassay data generated from the IERL-RTP phased environmental assessment methodology, corrolated with chemical analytic results. Limited bioassay data are available, and few data are directly comparable so far. Bioassay screening and test regimens are constantly under going improvement and revision, and as more comprehensive sampling and

analysis of FBC emission streams is accomplished, more comprehensive, relevant data will be available. Until such data are available for scrutiny, conclusions made would be highly speculative.

REFERENCES

1. The Fuels Use Act of 1978. Public Law No. 95-620, 92 Stat. 3290.

2. Newby, R.A., et al. Effect of SO_2 Emission Requirements on Fluidized-Bed Combustion Systems: Preliminary Technical/Economic Assessment. Prepared for the U.S. Environmental Protection Agency by Westinghouse Research and Development Center. EPA 600/7-78-163. August 1978.

3. Ibid. p. 24

4. Ibid. p. 59

5. Ibid. p. 24

6. Young, C.W., J.M. Robinson, C.B. Thunem, and P.F. Fennelly. Technology Assessment Report for Industrial Boiler Applications: Fluidized-Bed Combustion. Draft Final Report. Prepared for the U.S. Environmental Protection Agency Industrial Environmental Research Laboratory by GCA/Technology Division. July, 1979.

7. Hoke, R.C., R.R. Bertrand, M.S. Nutkis, L.A. Ruth, M.W. Gregory, E.M. Magee, M.D. Loughnane, R.J. Madon, A.R. Garabrant, and M. Ernst. Mini-plant Studies of Pressurized Fluidized-Bed Coal Combustion: Third Annual Report prepared by EXXON Research and Engineering Company for the U.S. Environmental Protection Agency, EPA-600/7-78-069. April 1978. pp. 203-210.

8. Jonke, A.A. et al. Reduction of Atmospheric Pollution by the Application of Fluidized-Bed Combustion, Annual Reports, July 1969 - July 1971. Prepared by Argonne National Laboratory. ANL/ES-CEN-1001, 1002 and 1004.

9. Robison, E.B., A.H. Bagnulo, J.W. Bishop, S. Ehrlich. Characterization and Control of Gaseous Emissions from Coal-Fired Fluidized-Bed Boilers. Prepared by Pope, Evans, and Robbins, Inc., for the U.S. Department of Health, Education and Welfare. October 1970.

10. Mesko, J.E., Multicell Fluidized-Bed Boiler Design Construction and Test Program, Quarterly Progress Report for October to December, 1975. Prepared by Pope, Evans, and Robbins., Inc., for the U.S. Energy Research and Development Administration, January 1976.

11. Hansen, W.A., et al. Fluidized-Bed Combustion Development Facility and Commercial Utility AFBC Design Assessment. Quarterly Technical Progress Reports, April 1978 to March 1979. Prepared by Babcock and Wilcox Company for the Electric Power Research Institute.

12. Beacham, B. and A.R. Marshal. Experiences and Results of Fluidized-Bed Combustion Plant at Renfrew. Prepared by Babcock Contractors Ltd., and Combustion Systems Ltd. Presented at a conference in Dusseldorf, W. Germany, November 6 and 7, 1978.

13. Hanson, H.A., D.G. DeCoursin, and D.D. Kinzler. Fluidized-Bed Combustor for Small Industrial Applications. Prepared by FluiDyne Engineering Corporation for the Fifth International Conference on Fluidized-Bed Combustion, December 1977. pp. 91-105.

14. FluiDyne Engineering Corporation. Industrial Application Fluidized-Bed Combustion Process, Quarterly Report, April-June 1977. Prepared by FluiDyne Engineering Corporation for the U.S. Energy Research and Development Administration (ERDA). FE 2463-12. November 1977. p 10.

15. Vogel, G. et al., A Development Program on Pressurized Fluidized-Bed Combustion. Prepared by Argonne National Laboratory, Annual Report for the U.S. Energy Research and Development Administration (ERDA). ANL/ES-CEN-1016. July 1975-June 1976. pp. 89-98.

16. Hoke, R.C., et al. op. cit. pp. 203-210.

17. Hoy, R. Pressurized Fluidized-Bed Combustion Report No. 43. Annual Report July 1976 - June 1977. Prepared by the National Research Development Corp., London, England for the U.S. Department of Energy (DOE) HCP/T-1511. p 33.

18. Hoke, R.C., et al. op. cit. p 52.

19. Newby, R.A., et al. op. cit. pp. 39-80.

20. Letter correspondence from Mr. D. Bruce Henschel of the U.S. EPA, IERL to Dr. Paul F. Fennelly of GCA/Technology Division.

21. Telephone correspondence between Mr. D.B. Henschel of the U.S. EPA, IERL and Mr. Charles W. Young of GCA/Technology Division.

22. Harvey, R.D., R.R. Frost, J. Thomas. Petrographic Characteristics and Physical Properties of Marls, Chalks, Shells, and Calcines related to Desulfurization of Flue Gases. Final Report prepared by the Illinois State Geological Survey for the U.S. Environmental Protection Agency. EPA-650/2-73-044.

23. Thoennes, C.M. Automatic Constant SO_2 Removal Concept Assessment. Monthly Progress Report, March 1979. Prepared by General Electric Company Energy Systems & Technology Division for the U.S. Environmental Protection Agency, p 1.

24. Jonke, A.A., G. Vogel, I. Johnston, S. Lee, J. Lenc, A. Lescarret, J. Montagna, F. Nunes, J. Shearer, R. Snyder, G. Smith, W. Swift, F. Teats, C. Turner, I. Wilson. Supportive Studies in Fluidized-Bed Combustion. Prepared by Argonne National Laboratory for the U.S. Environmental Protection Agency. EPA-600/7-77-138. December 1977, pp. 30-38.

25. Yang, R.T., M. Shen, and M. Steinberg. Fluidized-Bed Combustion of Coal with Lime Additives: Catalytic Sulfation of Lime with Iron Compounds and Coal Ash. Reported by the Department of Energy and Environment, Brookhaven National Laboratory, Upton, New York. Environmental Science and Technology. Volume 12, Number 8, August 1978, pp. 915-918.

26. Newby, R.A., D.L. Keairns. Alternatives to Calcium-based SO_2 sorbents for Fluidized-Bed Combustion: Conceptual Evaluation. Prepared by Westinghouse Research and Development Center for the U.S. Environmental Protection Agency, EPA-600/7-78-005. January 1978.

27. Johnson, I. Support Studies in Fluidized-Bed Combustion. Quarterly Report prepared by Argonne National Laboratory for the U.S. Department of Energy and the U.S. Environmental Protection Agency. ANL/CEN/FE 78-3. January to March, 1978.

28. Ruth, L.A. and G.M. Varga, Jr. Regenerable Sorbents for Fluidized-Bed Combustion. Final Report prepared by EXXON Research and Engineering Co. for National Science Foundation RANN Program. June 1978.

29. Hoke, R.C., et al. op. cit. pp. 48-51.

30. Ibid. pp. 203-210.

31. Curtiss-Wright Corporation. Engineer, Design, Construct, Test and Evaluate a Pressurized Fluidized-Bed Pilot Plant using high sulfur coal for production of electric power: Phase I Preliminary Engineering Annual Report. March 1, 1976 through February 28, 1977. Prepared by Curtiss-Wright Corp for the U.S. Energy Research and Development Administration (ERDA). FE-1726-17A March 15, 1977, pp. 2-25.

32. Hoy, R., op. cit. p 29.

33. Vogel, G.J., et al. op. cit. pp. 89-98.

34. Beacham, B., et al. op. cit.

35. Babcock and Wilcox Co. Fluidized-Bed Combustion Development Facility and Commercial Utility AFBC Design Assessment. Quarterly Technical Progress Report prepared for the Electric Power Research Institute RP-718-2-1, by Babcock and Wilcox Company. January-March 1979. pp. 2-5 to 2-90.

36. Lange, H.B., T.M. Sommer, C.L. Chen. SO_2 Absorption in Fluidized-Bed Combustion of Coal; Effect of Limestone Particle Size. Prepared by the Babcock and Wilcox Company for the Electric Power Research Institute. Report No. FP 667, January 1978.

37. Jonke, A.A. et al. op. cit.

38. Young, C.W., et al., op. cit. p 197.

39. Hoke, R.C., et al., op. cit. EPA-600/7-78-069, p 53.

40. Ando, J., et al. NO_x Abatement for Stationary Sources in Japan. Prepared by PEDCo for the U.S. Environmental Protection Agency. EPA-600/7-77-103b. September, 1977.

41. Personal Correspondence between Mr. Walter Steen of the U.S. Environmental Protection Agency and Mr. Cabot B. Thunem of GCA/Technology Division, March 20, 1979.

42. Hoke, R.C. A Regenerative Limestone Process for Fluidized-Bed Coal Combustion and Desulfurization, Monthly Progress Report No. 105. Prepared by EXXON Research and Engineering Company for the U.S. Environmental Protection Agency. November 1978.

43. Telephone correspondence between Mr. C.J. Lyons of Battelle Columbus Laboratories and Mr. Cabot B. Thunem of GCA/Technology Division, April 4, 1979.

44. Arthursson, D.A.A. Fluidized-Bed Furnace in Enköping, Sweden. Report No. 1. Description of Multi-Fuel Fluidized-Bed Furnace, prepared by Svenska, VärmeVerks-föreningen.

45. Beér, J.M. A.F. Sarofim, L.K. Chan, and A.M. Sprouse. NO Reduction by Char in Fluidized-Combustion. Massachusetts Institute of Technology, Department of Chemical Engineering and Energy Laboratory. Cambridge, Massachusetts. Undated, pp. 14-15.

46. Jonke, A.A., op. cit. ANL/ES-CEN-1002.

47. Parks, D.J. Formation of Nitric Oxide in Fluidized-Bed Combustion. PhD. Thesis. University of Minnesota, Department of Mechanical Engineering. 1973.

48. Robison, E.B., et al. op. cit.

49. Argonne National Laboratories. Annual Report. Report Number ANL/ES-CEN-1005. June 1973.

50. National Coal Board. Reduction of Atmospheric Pollution, Main Report. Prepared for the U.S. Environmental Protection Agnecy. Reference No. DHB 060971. September, 1971.

51. Hansen, W.A., et al. op. cit.

52. National Coal Board, op. cit.

53. Lange, H.B., et al. op. cit. p A-6.

54. Hoke, op. cit. EPA-600/7-78-069. April 1978, pp. 56-57.

55. Hoke, R.C., et al. Miniplant and Bench Studies of Pressurized Fluidized-bed Combustion: Final Report. Prepared by Exxon Research and Engineering Co., Linden, NJ for the U.S. Environmental Protection Agency. Report EPA-600/7-80-013, January 1980.

56. Hoy, R. op. cit. p 64.

57. Shackleton, M.A., et al. Ceramic Filter Tests at the EPA/EXXON PFBC Miniplant. Proceeding of The Second Symposium on the Transfer and Transfer and Utilization of Particulate Control Technology. July 23-27, 1979.

58. Monthly Progress Report. Environmental Assessment/Systems Analysis of the Fluidized-Bed Combustion Process. Prepared for the U.S. Environmental Protection Agency by GCA/Technology Division. September 10, 1979.

59. Davison, R.L., Natusch, D.F.S., Wallace, J.R., and C.A. Evans, Jr. (1974) Environmental Science and Technology, 8:1107, 1974

60. Natusch, D.F.S., Wallace, J.R., and C.A. Evans, Jr. Science 183:202, 1974.

61. Block, C. and Dams, R. Environmental Science and Technology 9:146, 1979.

62. Gladney, E.S., Small, J.A., Gordon, G.E., and W.H. Zoller. Atmospheric Environment 10:1071, 1976.

63. Pueschel, R.F. Geophysical Research Letters 3:651, 1976.

64. Campbell, J.A., Laul, J.C., Neilson, K.K., and R.D. Smith. Analytical Chemistry 50:1032, 1978.

65. Pitts, J.N., Grosjean, D., Mischke, T.M. Simmon, V.F., and D. Poole. Toxicology Letters 1:65, 1977.

66. Delinen, W., Pitz, N. and R. Tomingas. Cancer Letters 4:5, 1977.

67. Commoner, B., Modyastha, P. Bronsdon, A., and A.J. Vithayathel. Journal of Toxicology and Environmental Health 4:59, 1978.

68. U.S. Environmental Protection Agency, Environmental Science Research Laboratory. EPA-600/3-79-032, 1979, 14 pp.

69. Fisher, G.L., Chrisp, C.E., and W.G. Jennings. Presented at the 12th Annual Conference on Trace Substances in Environmental Health. June 5-8, 1978, University of Missouri. Columbia, Missouri.

70. Linton, R.W., Loh, A., Natusch, D.F.S., Evans, C.A., Jr., and P. Williams. Science 191:852, 1976.

71. Patterson, C.C. Archives of Environmental Health 11:344, 1965.

72. Davison, R.L., et al. op. cit.

73. Flagan, R.C. and Friedlander, S.K. Presented at the Symposium on Aerosol Science and Technology at the 82nd National Meeting of the American Institute of Chemical Engineers. August 29-September 1, 1976. Atlantic City, N.J.

74. Smith, R.D., Campbell, J.A., and K.K. Neilson. Environmental Science and Technology 13:533, 1979.

75. Swift, W.M., Vogel, G.L., and A.F. Panek. Potential of Fluidized-Bed Combustion for Reducing Trace Element Emissions. Presented at the 68th Annual Meeting of the Air Pollution Control Association, Boston, MA June 15-20, 1975.

76. Allen, J.M., Howes, J.E., Jr., Miller, S.E., and K.M. Duke (1977). Comprehensive Analysis of Emissions from Exxon Fluidized Bed Combustion Miniplant Unit. Prepared for the U.S. Environmental Protection Agency by Battelle Columbus Laboratories.

77. Lentzen, D.E., et al. IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition). Prepared by Research Triangle Institute for the U.S. Environmental Protection Agency. EPA-600/7-78-201. October, 1978.

78. Fisher, G.L., et al. op. cit.

79. Pillai, K.K. and Roberts, A.G. Emission Characteristics of a Pressurized Fluidized-Bed Coal Combustor. Prepared for the U.S. Environmental Protection Agency by the National Research Development Corporation, London, 1977.

80. Hoy, R. op. cit.

81. Young, C.W., et al. op. cit.

82. Pressurized Fluidized-Bed Combustion. British Coal Utilization Research Agency (BCURA), National Research Development Corporation, London. Prepared for Office of Coal Research. R&D Report No. 85.

83. Pope, Evans, and Robbins. Multicell Fluidized-Bed Boiler Design, Construction and Test Program. Pope, Evans, and Robbins, Inc. Publications No. PB 236 254/AS, Office of Coal Research, Washington, D.C. R&D Report No. 90 - Interim Report No. 1. August 1974.

84. Keairns, D.L., et al. Fluidized-Bed Combustion Process Evaluation; Phase II - Pressurized Fluidized-Bed Coal Combustion Development. Westinghouse Research Laboratories. Prepared for U.S. Environmental Protection Agnecy. EPA Report No. EPA-650/2-75-027c. September 1975.

85. Sun, C.C., C.H. Peterson, R.A. Newby, W.G. Vaux, D.L. Keairns. Disposal of Solid Residue from Fluidized-Bed Combustion: Engineering and Laboratory Studies. Prepared by Westinghouse Research and Development Center for the U.S. Environmental Protection Agency. EPA-600/7-78-049. March 1978.

86. Stone, R., and R.L. Kahle. Environmental Assessment of Solid Residues from Fluidized-Bed Fuel Processing, Final Report. Prepared by Ralph Stone and Company, Inc., for the U.S. Environmental Protection Agency, EPA-600/7-78-107, June 1978.

87. Sun, C.C., C.H. Peterson, D.L. Keairns, Environmental Impact of the Disposal of Processed and Unprocessed FBC Bed Material and Carry-over. Prepared by Westinghouse Research and Development Center for the 5th International Conference on Fluidized-Bed Combustion, p 5.

88. Sun, C.C., EPA-600/7-78-049, op. cit.

89. Sun, C.C., 5th International Conference on FBC, op. cit. p 5.

90. U.S. Environmental Protection Agency. Hazardous Waste Management System. Part III Identification and Listing of Hazardous Waste. Federal Register Vol. 45, No. 98, May 19, 1980. Book 2 of 3 books pp. 33063-33285.

91. Sun, C.C., EPA-600/7-78-049., op. cit.

92. Sun, C.C., 5th International conference on FBC, op. cit. p 5.

93. Stone, R. et al. op. cit.

94. Ibid. p 29.

95. Ibid. p 31.

96. Ibid. p 32.

97. The Resource Conservation and Recovery Act, op. cit.

98. Environmental Protection Agency - 40 CFR Part 250 Hazardous Waste Guidelines and Regulations: Federal Register Vol 43 No. 243 Monday, December 18, 1978.

99. Ibid.

100. Minnick, L.J. Development of Potential Uses for the Residue from Fluidized-Bed Combustion Processes. Quarterly Technical Progress Reports prepared for the U.S. D.O.E., by L.J. Minnick, Prime Contractor 1976 through 1979.

101. Telephone correspondence between Dr. H. Bennett, coordinator for DOE's Agricultural Program for FBC Solid Wastes, and Dr. T. Goldschmid of GCA/Technology Division, February 28, 1979.

102. Ibid.

103. Minnick, L.J. op. cit.

104. Technical Memorandum on Standard Support Activities for the Effluent Guidelines Division Under EPA's Fluidized-Bed Combustion Program. Submitted to the U.S. Environmental Protection Agency by GCA/Technology. July, 1979.

105. Ibid.

106. Allen, J.M., Howes, J.E., Jr., Miller, S.E., and K.M. Duke. Comprehensive Analysis of Emissions from Exxon Fluidized-Bed Combustion Miniplant Unit. Prepared for EPA-IERL-RTP by Battelle Columbus Laboratories. September 9, 1979.

107. Leutzen, D.E., et al. op. cit.

108. Cleland, J.G., and Kingsbury, G.L. Multimedia Environmental Goals for Environmental Assessment. Prepared by Research Triangle Institute for the U.S. Environmental Protection Agency Office of Research and Development. Washington, D.C. EPA-600/7-77-136a and b. November, 1977.

109. Allen, J.M., et al. op. cit.

110. Pillai, K.K. and Roberts, A.G. op. cit. p. 49

111. Fennelly, P.F., et al. Environmental Science Technology 11(3) 244-248, 1977.

112. GCA/Technology Division. Test Plan for the Level II Characterization of the Emissions from the EXXON Fluidized-Bed Combustion Miniplant. Prepared for the U.S. Environmental Protection Agency. Undated.

113. Cooper, H.B.H. and G.A. Dakik. Releases of Radioactive Isotopes from Coal and Lignite Combustion. Presented at the 71st Annual Meeting of the Air Pollution Control Association, June 25-20, 1978. Houston, Texas.

114. McBride, J.P., Moore, R.E., Witherspoon, J.P., and R.E. Blanco. Radiological Impact of Airborne Effluents of Coal and Nuclear Plants Science 202:1045-1050, 1978.

115. Dvorak, A.J. et al., The Environmental Effects of Using Coal for Generating Electricity. NUREG-0252, U.S. Nuclear Regulatory Commission, Washington, D.C., 1977.

116. Lee, H., Peyton, T.O., Steele, R.V., and R.K. White. Potential Radioactive Pollutants Resulting from Expanded Energy Programs, EPA-600/7-77-082, 1977.

117. Landstrom, D.K. Radionuclides from FBC Processes. Battelle Columbus Laboratories, Brief Technical Memo No. 3, 1977.

118. VanHook, R.H., Potential Health and Environmental Effects of Trace Elements and Radionuclides from Increased Coal Utilization. ORNL-5367, Oak Ridge National Laboratory, Chemical Technology Division, 1978.

119. Eisenbud, M. and H.G. Petrow. Radioactivity in the Atmospheric Effluents of Power Plants that Use Fossil Fuels, Science 144:288-289, 1964.

120. Martin, J.E., Harward, E.D., and D.T. Oakley. Comparison of Radioactivity from Fossil-Fuel and Nuclear Power Plants. Environmental Effects of Producing Electric Power-Part I, Appendix 14. Committee Print, Joint Committee on Atomic Energy, 91st Congress of the U.S. 1st Session, Washington, D.C., 1969.

121. Eisenbud, M. and H.G. Petrow, op. cit.

122. Martin, J.E., op. cit.

123. Klein, D.H. et al. Pathways of Thirty-seven Trace Elements through a Coal-Fuel Power Plant. Environ. Sci. Technol. 9:862864, 1975.

124. Kaakinen, J.W. et al. Trace Element Behavior in Coal-Fired Power Plants, Environ. Sci. Technol. 9:973-976, 1975.

125. Landstrom, D.K. op. cit.

126. Personal communication between Charles Amato of U.S. Environmental Protection Agency Office of Radiation Programs and R.J. Kindya. June, 1979.

127. Lee, H., et al., op. cit.

128. McBride, J.P., et al., op. cit.

129. Dvorak, A.J., et al., op. cit.

130. Lee, H., et al., op. cit.

131. Landstrom, D.K., op. cit.

132. Van Hook, R.I. op. cit.

133. Theis, T.L. et al. Field Investigation of Trace Metals in Groundwater from Flyash Disposal, J.Water Poll. Cont. Fed. 50(11), 2457-60, 1978.

134. Kindya, R.J. and R.R. Hall Radioassay of PFBC Miniplant Samples. Draft Final Report prepared by GCA/Technology Division, Bedford, Massachusetts for the U.S. Environmental Protection Agency.

135. Grimshaw, T.W., D.N., Garner, W.F. Holland, A.G. Lamkin, W.M. Little, R.M. Mann, and H.J. Williamson. Generation and Attenuation of Leachate from Fluidized-Bed Combustion Solid Waste-First Year Progress Report. Prepared by Radian Corp., Austin, Texas for the U.S. Environmental Protection Agency. Report No. EPA-600/7-80-095, May 1980.

136. Duke, J.M., Davis, M.E., and A.J. Dennis, IERL-RTP Procedures Manual: Level 1, Environmental Assessment Biological Tests for Pilot Studies. Prepared by Battelle Columbus Laboratories for the U.S. Environmental Protection Agency, Office of Research and Development, EPA-600/7-77-043. April, 1977.

137. Ibid.

138. U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Process Measurements Review, Volume 1 Number 4, Spring Edition 1975, p 9.

139. Allen, J.M., op. cit.

140. Clark, C.R., Hanson, R.L., and A. Sanchez. Mutagenicity of Effluents Associated with the Fluidized-Bed Combustion of Coal. Inhalation Toxicology Research Institute Annual Report 1977-1978. pp. 277-284. Prepared for U.S. Department of Energy under contract No. EY-76-C-04-1015.

141. Hill, J.O. and C.E. Mitchell. In Vitro Cytotoxicity of Potential Effluents from the Fluidized-Bed Combustion and Low-BTU Gosification of Coal. Inhalation Toxicology Research Institute Annual Report 1977-1978 pp. 290-293. Prepared for U.S. Department of Energy under Contract No. EY-76-C-04-1015.

142. Allen, J.M., Merryman, E.L., Howes, J.E., Jr., Miller, S.E. and E.J. Schultz. Comprehensive Analysis of Emissions from MERC Fluidized-Bed Combustion Unit. Draft Report prepared by Battelle Columbus Laboratories for the U.S. Environmental Protection Agency.

143. Kubitschek, H.E., Haugen, D.A., Venters, D. and D. Williams. Interim Progress Report on FBC Mutagenesis Studies as reported in Proceedings of a Workshop on Fine Particulate Emissions from Fluidized-Bed and Conventional Combustion. Sponsored by U.S. Department of Energy, Office of Health and Environmental Research held October 23-24, 1978, Washington, D.C. Published August 1979. CONF-7810153.

144. J.L. Epler et al. Toxicity of Leachates - Interim Progress Report April, 1978-January 1, 1979. Prepared for the U.S. Environmental Protection Agency, Office of Solid Waste by Oak Ridge National Laboratory.

145. Personal communication between H.E. Kubitschek of Argonne National Laboratory and R.J. Kindya of GCA/Technology Division.

146. Chrisp, C.E., Fisher, G.L., and J.E. Lammert. Mutagenicity of Filtrates from Respirable Coal Fly Ash, Science 199:73-75, 1978.

147. U.S. Environmental Protection Agency, Health Effects Research Laboratory. Interagency Progress in Energy-Related Health and Environmental Effects Research. EPA-600/7-79-009, January, 1979.